Acerca de este libro

Esta es una copia digital de un libro que, durante generaciones, se ha conservado en las estanterías de una biblioteca, hasta que Google ha decidido escanearlo como parte de un proyecto que pretende que sea posible descubrir en línea libros de todo el mundo.

Ha sobrevivido tantos años como para que los derechos de autor hayan expirado y el libro pase a ser de dominio público. El que un libro sea de dominio público significa que nunca ha estado protegido por derechos de autor, o bien que el período legal de estos derechos ya ha expirado. Es posible que una misma obra sea de dominio público en unos países y, sin embargo, no lo sea en otros. Los libros de dominio público son nuestras puertas hacia el pasado, suponen un patrimonio histórico, cultural y de conocimientos que, a menudo, resulta difícil de descubrir.

Todas las anotaciones, marcas y otras señales en los márgenes que estén presentes en el volumen original aparecerán también en este archivo como testimonio del largo viaje que el libro ha recorrido desde el editor hasta la biblioteca y, finalmente, hasta usted.

Normas de uso

Google se enorgullece de poder colaborar con distintas bibliotecas para digitalizar los materiales de dominio público a fin de hacerlos accesibles a todo el mundo. Los libros de dominio público son patrimonio de todos, nosotros somos sus humildes guardianes. No obstante, se trata de un trabajo caro. Por este motivo, y para poder ofrecer este recurso, hemos tomado medidas para evitar que se produzca un abuso por parte de terceros con fines comerciales, y hemos incluido restricciones técnicas sobre las solicitudes automatizadas.

Asimismo, le pedimos que:

+ *Haga un uso exclusivamente no comercial de estos archivos* Hemos diseñado la Búsqueda de libros de Google para el uso de particulares; como tal, le pedimos que utilice estos archivos con fines personales, y no comerciales.

+ *No envíe solicitudes automatizadas* Por favor, no envíe solicitudes automatizadas de ningún tipo al sistema de Google. Si está llevando a cabo una investigación sobre traducción automática, reconocimiento óptico de caracteres u otros campos para los que resulte útil disfrutar de acceso a una gran cantidad de texto, por favor, envíenos un mensaje. Fomentamos el uso de materiales de dominio público con estos propósitos y seguro que podremos ayudarle.

+ *Conserve la atribución* La filigrana de Google que verá en todos los archivos es fundamental para informar a los usuarios sobre este proyecto y ayudarles a encontrar materiales adicionales en la Búsqueda de libros de Google. Por favor, no la elimine.

+ *Manténgase siempre dentro de la legalidad* Sea cual sea el uso que haga de estos materiales, recuerde que es responsable de asegurarse de que todo lo que hace es legal. No dé por sentado que, por el hecho de que una obra se considere de dominio público para los usuarios de los Estados Unidos, lo será también para los usuarios de otros países. La legislación sobre derechos de autor varía de un país a otro, y no podemos facilitar información sobre si está permitido un uso específico de algún libro. Por favor, no suponga que la aparición de un libro en nuestro programa significa que se puede utilizar de igual manera en todo el mundo. La responsabilidad ante la infracción de los derechos de autor puede ser muy grave.

Acerca de la Búsqueda de libros de Google

El objetivo de Google consiste en organizar información procedente de todo el mundo y hacerla accesible y útil de forma universal. El programa de Búsqueda de libros de Google ayuda a los lectores a descubrir los libros de todo el mundo a la vez que ayuda a autores y editores a llegar a nuevas audiencias. Podrá realizar búsquedas en el texto completo de este libro en la web, en la página `http://books.google.com`

This is a reproduction of a library book that was digitized by Google as part of an ongoing effort to preserve the information in books and make it universally accessible.

Google™ books

https://books.google.com

MERCURY-ARC RECTIFIERS AND MERCURY-VAPOUR LAMPS

J. A. FLEMING
M.A., D.Sc., F.R.S.

Digitized by Google

Library
of the
University of Wisconsin

Digitized by Google

TRANSFERRED TO
MEMORIAL LIBRARY

Digitized by Google

Digitized by Google

MERCURY-ARC RECTIFIERS
AND
MERCURY-VAPOUR LAMPS

Digitized by Google

FROM THE SAME PUBLISHERS.

An Introduction to Wireless Telegraphy and Telephony

By Professor J. A. Fleming, M.A., D.Sc., F.R.S. This book is intended for the general reader, i.e. the "listener in," who takes more than a casual interest in wireless. Professor Fleming gives a brief sketch of the general principles of wireless telegraphy and telephony as at present operated, which will serve as an introduction to the more advanced books on the subject.

In crown 8vo, 120 pp., illustrated. **3s. 6d.** net.

The Electrolytic Rectifier

By N. A. de Bruyne. A useful survey of present-day theory and practice. For electrical engineers, physicists, and wireless amateurs. The book contains full information as to how to make and use a rectifier for charging accumulators from alternating current supply mains.

Contents: Characteristics of Electrolytic Rectifiers—Theory of Electrolytic Rectifiers—Applications and Methods of Connection—Electrolytic Lightning Arresters—How to Make a Rectifier for Accumulator Charging.

In crown 8vo, with 23 illustrations. **3s. 6d.** net.

Digitized by Google

MERCURY-ARC RECTIFIERS
AND
MERCURY-VAPOUR LAMPS

BY

J. A. FLEMING, M.A., D.Sc., F.R.S.

University Professor of Electrical Engineering in the University of London
Honorary Member of the Institution of Electrical Engineers, London
Honorary Member of the Royal Engineers Institute, Chatham
Albert Medallist of the Royal Society of Arts, London
Member of the Royal Institution of Great Britain
Sometime Fellow of St. John's College
Cambridge: Fellow of University
College, London, etc., etc.

LONDON
SIR ISAAC PITMAN & SONS, LTD.
PARKER STREET, KINGSWAY, W.C.2
BATH, MELBOURNE, TORONTO, NEW YORK
1925

Digitized by Google

PRINTED IN GREAT BRITAIN
AT THE PITMAN PRESS, BATH

Digitized by Google

302222
MAR 26 1926
TOD
·F62
M

FOREWORD

THE present little book was written at the request of Messrs. Sir Isaac Pitman & Sons, Ltd., to supply a small treatise on the mode of operation and uses of the mercury-arc rectifier and mercury-vapour lamps.

Now that this rectifier has been converted into an appliance available for electrical work on the large scale involved in electric traction and electric technology, and has reached a durability and efficiency on a level with that of the highest class of dynamos, static transformers, or motor generators, it is very desirable that all electrical engineers should be acquainted with its use and working. The mercury-vapour lamp in a silica bulb has also at present very important medical uses as a therapeutic agency.

The Author desires to place on record his obligations to Messrs. Brown, Boveri & Co., of Baden, Switzerland, for supplying information on their all-metal mercury rectifiers, and to Mr. R. L. Morrison, A.M.I.E.E., for kindly permitting use to be made of the information and diagrams on this appliance in a pamphlet by him issued by Messrs. Power-Rectifiers, Ltd., of Waterloo Place, London. Also to express his thanks to the Hewittic Electric Company, of Hersham, Walton-on-Thames, Surrey, England, for permission to use diagrams and for supplying information on the Cooper Hewitt Mercury-vapour Lamps and Rectifiers made by them. Also to Messrs. Watson & Sons, and to Messrs. Siebe, Gorman & Co., Ltd., for their courtesy in supplying blocks for illustrations taken from their technical publication and circulars.

J. A. F.

Digitized by Google

Digitized by Google

CONTENTS

PAGE

FOREWORD v

CHAPTER I

THE TRANSMISSION OF ELECTRICITY THROUGH GASES AND VAPOURS 1

1. The atomic constitution of matter—2. The atomic constitution of electricity—3. Modern views of the structure of atoms and isotopes. Definition of the terms atomic number and atomic weight—4. Nature of an electric discharge in a gas and varieties of electric discharge, spark, glow, and arc.

CHAPTER II

THE ELECTRIC-ARC DISCHARGE 13

1. The nature of the electric-arc discharge; First production of the electric arc by Sir Humphry Davy at the Royal Institution; Manufacture of carbons for the electric arc—2. The transport of ions taking place in the arc; The relation of voltage and arc length—3. The characteristic curve of the arc or relation of current and voltage.

CHAPTER III

THE MERCURY-ARC LAMP 24

1. The electric arc between mercury electrodes; The Mercury-vapour lamp; The mercury atom and ion—2. The Cooper Hewitt mercury-vapour lamp; Various types manufactured by the Hewittic Electric Company and others—3. Various uses of the mercury-vapour lamp.

CHAPTER IV

THE MERCURY-ARC RECTIFIER 42

1. The unilateral conductivity of the mercury-arc between a mercury cathode and iron or graphite anode—2. The single-phase glass bulb mercury rectifier; Types

Digitized by Google

PAGE

manufactured by the Hewittic Electric Company; the relation of the rectified and applied voltage—3. The three-phase and the six-phase mercury rectifiers; Numerical ratio of rectified to applied voltage—4. The efficiency of the mercury-vapour rectifier.

CHAPTER V

THE MERCURY-VAPOUR RECTIFIER IN ELECTRICAL ENGINEERING 60

1. Types of rectifier used in electrical work; Glass bulb and all-metal rectifiers—2. The Hewittic Company's equipment for rectification of alternating electric currents —3. Large rectifier sub-stations for traction and battery charging work—4. The Brown, Boveri Company's all-metal high and low-voltage rectifiers; General arrangements; Methods of making and testing the vacuum; Vacuum pumps and gauges.

CHAPTER VI

THE MERCURY-ARC GENERATOR 89

1. The mercury rectifier as a generator of electric oscillations of high frequency—2. The Vreeland Oscillator and its mode of operation—3. Three-electrode mercury valves and their operation; The difference between ionic and thermionic rectifiers and valves in their mode of operation and uses—Conclusion.

LIST OF INSET PLATES

FIG.		*bet. pp.*
26a.	Efficiency Curves of Mercury-vapour Rectifier .	64–65
31.	Section of the Brown, Boveri All-metal Mercury-vapour Rectifier for High Tension Alternating (Three-phase) Current	76–77
38a.	Scheme of Circuits for Six-phase B.B. Mercury-vapour Rectifier	86–87
39.	1,000 Kilowatt Mercury Rectifier	86–87

Digitized by Google

MERCURY-ARC RECTIFIERS
AND
MERCURY-VAPOUR LAMPS

CHAPTER I

THE TRANSMISSION OF ELECTRICITY THROUGH GASES AND VAPOURS

1. **The Atomic Constitution of Matter.** In the latter half of the nineteenth century a question which was much discussed was the nature of electricity. In earlier times electricity was regarded as an imponderable fluid or as something without mass or inertia and intangible. Heat, or as it was then called, caloric, was also classified under the same heading, but the evidence which had accumulated showing that sensible heat consists in a vibratory motion of material atoms, and the demonstration that it can be evaluated in terms of mechanical energy or in foot-pounds, showed that it must be regarded as a form or type of energy of motion. Certain incautious writers were then led to speak of electricity as a form of energy. This, however, is not the case. The specification and measurement of energy in all its forms involves two factors, and the energy is measured by their product. Thus, when we raise a weight against the force of gravity we do " work " or store up potential energy, and this energy is measured by the product of weight raised and height through which it is raised. In like manner, when we charge a conductor with electricity we do work and store up potential energy. The energy is measured by the product of the quantity of the electricity and the mean potential through which the charge

Digitized by Google

is raised. Hence, electricity cannot be a form of energy because quantity of electricity is only one of the factors in the measurement of energy in the form of electric charge.

It was not until the close of the nineteenth century that it became evident that electricity is more a form of substance than a form of energy, and that like material substances it is atomic in structure.

The whole of the chemical research of the last century had shown that material substances, even elementary or simple substances, are not infinitely divisible, but that there is a smallest unit called a *molecule* or an *atom* which is the ultimate limit of the division of matter without change of properties.

Thus, chemical facts show that the substance called Epsom salts is not a simple body, but a compound of the metal magnesium and of the non-metals sulphur and oxygen. If we could divide a quantity of it into smaller and smaller parts, we should ultimately arrive at a smallest portion which presents the chemical characteristics of this substance called sulphate of magnesium. This is called a *molecule* of the substance. Then, furthermore, if we could divide up a mass of metallic magnesium we should finally reach a limit or smallest part of this element which would possess the chemical qualities of magnesium, and this is called an *atom* of magnesium.

Before the end of the nineteenth century no one had been able to carry the division of matter any further than the chemical atom, but the study of the passage of electricity through gases led Sir Joseph Thomson to the astonishing discovery that chemical atoms themselves can be broken up, and it was ultimately rendered probable that all of the eighty-seven or eighty-eight kinds of atom, however different in chemical qualities, are composed of two constituents, now called *electrons* and *protons*, arranged in various ways. Whether progressive scientific research will enable us to explore the nature of electrons and protons

Digitized by Google

no one can yet say, but at present we find in them, as far as we yet know, the ultimate constituents of which our material universe is composed. We may say, then, that so far as the things we can see or handle and which have weight, the stages of construction are as follows—

Electrons and protons build up atoms when arranged in a certain way. Atoms grouped in various modes form molecules, and molecules gathered together compose masses, which may be crystalline when the molecules are regularly arranged or amorphous when otherwise collected. Then, finally, material masses present themselves as *solids* when the molecules cohere so that the mass keeps its form or shape irrespective of any containing vessel, as *liquids* when the molecules can move freely amongst each other but still exert a certain mutual attraction which keeps them in contact, and as gases or vapours when the molecules or atoms no longer exert attraction or keep in contact, but are moving with great velocity in an irregular manner with varying speeds and fill up any vessel in which the gas is placed. Hence, we may say that solids, unless finely divided up, have constant bulk and shape irrespective of any containing vessel. Liquids take the shape of the containing vessel, but retain a constant bulk or volume irrespective of the size of the vessel. Gases have neither constant volume nor shape, but fill up any closed vessel in which they are placed and exert a pressure on all its walls.

2. **Atomic Constitution of Electricity.** Perhaps the most important physical discovery made in the first half of the eighteenth century was that due to the brilliant French investigator, Charles Francois de Cisternay Dufay, who, in his brief lifetime of 41 years, contributed largely to scientific and especially to electrical knowledge. Dufay was the first to prove that there are two kinds of electricity, and that the electricity produced by rubbing glass with silk, now called positive, is different from that obtanied by rubbing resin with flannel, which is called negative electricity.

Digitized by Google

The most suggestive electrical discovery made at the close of the nineteenth century was that of Sir Joseph Thomson, viz. that we can extract from all material atoms certain identical and very small particles which are named *electrons*, and that these, taken collectively, constitute the electricity we call negative.

If a neutral chemical atom is deprived of one or more of its electrons it is left in a condition in which it exhibits a so-called positive electrification. If it gains or takes up electrons, then it becomes negatively electrified.

A neutral chemical atom which has lost one or more electrons and exhibits positive electrification is called *a positive ion.* A neutral atom or group of atoms which has gained electrons over and above the number required to render it electrically neutral is called *a negative ion*, and this term is also sometimes applied to a free or single electron.

We do not know as much about the protons, which are the other constituent of chemical atoms, or whether we have the right to say that protons taken together constitute positive electricity in the same way that electrons taken together constitute negative electricity.

We can, however, state that particles of negative electricity go to build up chemical atoms of matter in conjunction with other particles called protons. Accordingly, electricity is atomic in structure in the sense that there is an ultimate indivisible element or particle of it, at least indivisible by us at present.

Electricity and so-called matter are therefore intimately connected, and the material substances we can see, handle, and weigh may be built up of nothing but particles of electricity of two kinds.

3. **Modern Views of Atomic Structure.** It is necessary to refer a little more in detail to modern views as to the structure of chemical atoms. This branch of knowledge has progressed in a wonderful degree of late years. It is not long since our scientific conception of an atom was that

Digitized by Google

it was an infinitely hard, indivisible little mass, concerning the inner nature of which we know nothing. At present we seem able to explore its dimensions and structure with ever-increasing insight into its mechanism.

Broadly and generally speaking, a chemical atom is now regarded as a solar system in miniature. It has a central core called the nucleus, around which are placed, and probably revolve in various orbits, a number of electrons like planets round the sun.

This nucleus is composed of protons and electrons held together by strong mutual attractions. It is very much smaller than the atom itself and by far the greater part of the mass, or as we call it the weight, of the atom resides in the nucleus and particularly in the protons.

Each proton in the nucleus contributes a unit of mass and a unit of positive charge to the atom. Around the nucleus in a neutral atom circulate planetary electrons in number equal to the difference between the number of protons and electrons in the nucleus. This number of planetary electrons is called the *atomic number*, which may perhaps be better defined as the number of free or resultant positive units in the nucleus. The total number of protons corresponds closely to the *atomic weight* of the atom.

The chemical properties of the atom depend chiefly on its atomic number. Hence it is possible to have atoms of different atomic weights, but the same atomic number, and therefore having essentially the same properties, and denoted by the same name.

For if we can deprive the nucleus of one or more electrons without altering the number of protons the atomic number will be changed, but the atomic weight will remain the same, or nearly the same, and the chemical properties will be changed. On the other hand, we can have atoms with the same chemical properties but slightly different atomic weights. These are called *isotopes*. Thus, there are two kinds of lithium atom of atomic weights 6 and 7, two kinds

Digitized by Google

of boron atom with weights 10 and 11, two varieties of chlorine atom of atomic weights 35 and 37. But there is only one sort of atom of phosphorus (31), carbon (12), fluorine (19), sodium (23), and sulphur (32). There are, however, six kinds of krypton atom, five of tin, probably, four of mercury, and several isotopes of lead.

The atomic numbers vary from 1 for the hydrogen atom with atomic weight 1·008 (oxygen = 16) to uranium with atomic number 92 and atomic weight 238·2.

Elements for which the atomic weight is an integer number have probably no isotopes, whereas such an element as chlorine, of which the mean atomic weight is 35·46, is a mixture of the two isotopes of chlorine or two sorts of chlorine atoms with atomic weights 35 and 37 respectively.

The nuclei of those elements which are composed of a large number of protons and electrons, and therefore having large atomic weights, appear to be unstable and to break up spontaneously. These elements are called *radio active*, and they include the elements radium, thorium, uranium, and others. Then as regards the relative masses of the protons and electrons, it has been shown by the work of Sir J. J. Thomson and others that the unit or atom of negative electricity, that is one electron, has a mass of $\frac{1}{1850}$th of that of a hydrogen atom.

We know, however, that 11,200 cubic centimetres of hydrogen at 0° C. and 760 mm. weighs 1 gram and also that 1 cub. cm. of hydrogen gas at this temperature and pressure contains fifty-four million billion atoms ($= 54 \times 10^{18}$). Hence 6×10^{23} atoms of hydrogen weigh 1 gram, and, accordingly, the mass of one electron or atom of negative electricity is $\frac{1}{11 \times 10^{26}}$ of a gram, or 1,100 billion billion electrons weigh 1 gram. (*Note.*—One billion in English reckoning means a million times a million.)

It is a truly remarkable discovery to have found that

Digitized by Google

electricity has mass or, in common language, weight. The quantity of electricity called 1 coulomb, which is the quantity conveyed by a current of 1 ampere in 1 second, is equal to six million billion electrons, or 6×10^{18} electrons nearly. Therefore 200 coulombs of negative electricity weigh nearly one-millionth of a gram.

We may put the result in another way. If an electric current of 1 ampere were to flow in a wire for 50 hours, or about two days and nights, the quantity of electricity in the form of electrons which would have crossed any section of that wire would weigh 1 milligram, or one-thousandth part of a gram. Electricity, therefore, has weight or mass or inertia just as material substance has, and we can measure out and speak of an ounce of negative electricity just as we can weigh out and speak of an ounce of tobacco or tea.

The unit of positive electricity has, however, nearly 2,000 times the mass of the negative, unit for unit or proton for electron, and the mass or inertia or weight of ordinary material substances is nothing else than the mass, inertia, or weight of the electricity, chiefly the positive, of which that matter is composed.

Matter in motion possesses kinetic energy or energy of motion, and electricity in motion or an electric current also possesses kinetic energy.

We can then attempt to form a mental picture of the structure of an atom in accordance with the so-called Bohr-Rutherford hypothesis based on the researches of Professor Niels Bohr and Sir Ernest Rutherford as follows—

An atom of hydrogen consists of a single proton around which revolves a single electron, or rather the two revolve round their common centre of mass. Inasmuch, however, as the proton has 1,830 times the mass of the electron, that centre of mass is quite near the proton.

The peculiar feature, however, in Bohr's atomic theory is that he supposes the electron cannot revolve at any or every distance from the proton, but only in certain elliptical

Digitized by Google

paths called *quantum paths*, and that these paths or orbits are characterized by the fact that in changing from one to the other orbit the angular momentum of the electron changes by an integer multiple of a certain very small unit of angular momentum, and when revolving in a quantum path the electron does not lose or radiate energy, but only when it jumps from one quantum path to another.

In the ordinary classical dynamics when a planet revolves round its sun there is no reason why it should revolve at any particular distance or radius for its orbit. Its distance and time of revolution are, however, connected by Kepler's Third Law, viz. that the square of the time of revolution divided by the cube of the mean distance of revolution is a constant quantity. In the atomic astronomy, however, the revolving electron is not free to choose any orbit or distance of revolution round its nucleus or any time of revolution, but it must revolve in a certain quantum path. The reason for this is not yet known.

The planetary electrons which revolve round the nucleus are distributed in certain concentric shells or layers. It is extremely unlikely that they revolve in one plane, yet for the sake of simplicity in drawing and describing atoms, we speak of these orbits as if they were rings described round the nucleus as centre. The orbit nearest the nucleus is called the K-ring, the next the L-ring, and M-, N-, etc., are the remaining rings in order outwards.

If, then, any stray electron or positive ion strikes against an atom with sufficient velocity and in a certain direction it may penetrate into that atom's family circle of electrons, and may knock an electron out of some one of the orbits. When this is the case the injured atom tries to pick up an electron to re-complete its ring, and an electron from outside may be drawn in and find its home in the ring from which another electron had been knocked out. Atoms like to have their family circle of electrons complete, and if one escapes or is carried off they sooner or later adopt

Digitized by Google

another child. The newcomer settles down to its proper position with certain oscillations, and these create electric waves of a certain definite frequency. When we analyse this radiation by means of a prism or diffraction grating we can photograph or see a certain line in that spectrum which is called a K-line or L-, M-, or N-line, etc., according to the ring in which the arriving electron finds its place.

The arriving electron radiates energy in falling back into a vacant place in an atomic orbit, and to extract or remove an electron from its orbit we have to " do work " or supply energy from outside.

The vibrations set up when an electron falls back into the K-ring are extremely rapid and produce the so-called X-ray spectrum, whilst the vibrations due to electrons arriving in the outer rings give rise to the lines photographed or seen in the ultra-violet or in the visible part of the spectrum. Suppose, then, that we have a mixture of neutral atoms of a particular kind, and that mingled with these are free electrons and also neutral atoms which have lost one or more planetary electrons and become therefore positive ions.

Let us, then, assume that an electric force is caused to act on this mixture. This electric force may be supplied by placing two metal plates called electrodes in this mixture of atoms, ions and electrons, and creating a difference of potential between these plates or voltage by a battery or induction coil or other means.

When this is done the negative ions or the electrons in the mixture begin to work their way towards the positive electrode or anode, and the positive ions migrate towards the negative electrode or cathode.

Any particular ion or electron may not get very far before it picks up an electron or penetrates into an ionised atom, and its place is then taken by another free electron or ion. But on the whole there is a double movement in opposite directions, and this constitutes an electric current

Digitized by Google

in the gas or electric discharge. The current density is measured by the quantity of electricity conveyed per second normally through 1 sq. cm. of the field.

4. **Varieties of Electric Discharge.** If two metal electrodes are immersed in a more or less rarified gas and kept at a sufficiently high and constant potential difference, we generally obtain a form of electric current through the gas accompanied by luminosity called a *glow discharge*, which presents various appearances according to the pressure of the gas. In the glow discharge the electrodes do not contribute very copiously ions or electrons from their own substance. Suppose, for instance, that the medium consists of slightly rarified hydrogen or air in a glass tube with metal wires sealed into the ends as electrodes, and that these electrodes are connected to an electrical machine or induction coil which keeps them at a large potential difference. What happens is as follows—

In such a vessel there are always a certain number of free electrons or ions derived perhaps from the walls of the tube. The electric force between the electrodes causes movement of these ions, and by collisions between them and the gas molecules more ions are produced.

The phenomena presented, however, by electric discharge in rarified gases are very complicated, and have been made the subject of profound study by some of the greatest physical investigators. If two electrodes in the form of wires are sealed into the ends of a glass tube filled with air or gas under a reduced pressure of a millimetre of mercury or less, and if these electrodes are brought to a potential difference of several thousand volts by an electrical machine or induction coil, then we observe the following effects.

The negative electrode or wire is covered with a luminous glow like a coating, and beyond this is a dark space called the Crookes dark space from its discoverer Sir William Crookes. Beyond this dark space on the way to the anode there is a faint luminous glow, called the negative glow,

Digitized by Google

occupying a certain length of the tube, and then beyond that another dark space called the Faraday dark space. Then beyond this another luminous glow, called the positive column or light, which extends all the way up to the anode, and in some conditions as regards pressure and current is divided up into bright and dark spaces called striations. The colour of this positive column depends on the nature of the gas.

We shall not attempt to give full explanations of this complicated appearance of the glow discharge in a rarified gas, but refer the reader to books such as that of Sir J. J. Thomson on *Conduction of Electricity Through Gases* for them.

Suffice it to say that the effects are essentially due to an ionization of the gas which begins near the cathode.

There is a very rapid increase of potential as we leave the cathode on the way to the anode, and any free electrons which are at that place are driven violently against molecules of the gas and ionize them. The positive ions so produced are drawn back to the cathode and ionize the layer of gas on it and thus create more electrons. There is then a very rapid ionization and de-ionization of the gas layer close to the cathode, and this produces luminous radiation which we see as the cathode glows.

It is also a region where ions and electrons are being formed, and the electrons are driven away from the cathode, and by ionization of the gas produce all the complicated phenomena of the glow discharge in the tube. It is not necessary for the purpose of this little book to discuss them in detail.

Then in the next place there is a form of electric discharge called the *spark discharge*. This takes place when the electrodes are raised to a high potential but have such a small rate of supply of electricity given to them that a current started through the gas lowers very rapidly the potential of the electrodes.

Digitized by Google

In this case the discharge begins, then stops, and then begins again, and so forth. In this discharge the electrons which ionize the gas molecules are produced from the cathode by the bombardment of positive ions. The process begins by the ionization of gas molecules by some electrons or ions already present in the gas. Hence there is a certain delay or lag in the true spark discharge making its appearance. The electrodes are themselves disintegrated when the true spark begins, and the spectrum of the light of the discharge contains lines due to the metal of the electrodes as well as dependent on the nature of the gas in which they are contained.

The voltage at which the true spark discharge takes place is independent of the metals used as electrodes except, perhaps, in the case of aluminium, but it depends greatly on the form and size of the electrodes and on the pressure of the gas.

Approximately speaking, the voltage V required to produce a moderately long spark between balls of a certain diameter with adjacent surfaces d centimetres distant is of the form

$$V = a + bd$$

where a and b are constants depending on the nature of the gas, its pressure, and the diameter of the balls.

At atmospheric pressure and for air the value of a in the above formula is nearly 1,500 and b is nearly 30,000 when V is in volts and d in centimetres. Hence a voltage of 31,500 volts will produce a spark 1 cm. long in air at 760 mm. pressure between metal balls about 2 cm. in diameter.

As we are not concerned in this little book with spark discharges we shall not occupy space with further discussion of the spark discharge, but deal in the next chapter with that variety of electric discharge called the *arc discharge*, which takes place when the supply of electricity to the electrodes is sufficiently copious to cause considerable heating of them and consequent volatilization.

Digitized by Google

CHAPTER II

THE ELECTRIC-ARC DISCHARGE

1. **The Electric-arc Discharge.** When two metallic electrodes are placed in contiguity in a gas either at normal or reduced pressure, it will in general require a large difference of potential between these electrodes, perhaps many hundreds or thousands of volts, to start and maintain either the glow or the spark discharge already described. The current also will be small, perhaps a fraction of a milliampere, and in order that this form of discharge may continue the current must be kept small either by the resistance of the gaseous medium itself or by external resistance in the circuit of the electromotive force.

In the glow and spark discharge the material of the electrodes is not very much disintegrated or worn away or volatilized. We can, in fact, take electric sparks for years between a pair of metal balls and find very little evidence that metal has been removed from them except by a little pitting or roughness of their surface.

In the same manner a so-called vacuum tube exhibiting the glow discharge between aluminium or platinum electrode wires sealed through the glass will act for years without sensible deterioration of the electrodes.

If, however, the source of electromotive force, instead of having very high internal resistance such as an electrical machine or induction coil, or having some high resistance in series with it, has a very low internal resistance such as a dynamo, transformer, primary or secondary battery, and if the electrodes, especially the negative electrode, are kept hot, then the discharge rapidly passes into a type called the *Arc discharge*, in which the electrodes are rapidly disintegrated and the current between them becomes very

Digitized by Google

large, perhaps an ampere or scores of amperes. The electrodes soon rise to a very high temperature and great heat and light are radiated from them. The potential between the electrodes has therefore to be kept small, say, about 50 volts or so, or the arc current would soon become extremely large.

This form of arc discharge was first produced on a large scale by Sir Humphry Davy in the laboratories of theRoyal Institution of Great Britain, London, in 1808, using pieces of hard carbon as the electrodes in air at normal pressure.

On 11th July, 1808, Davy laid a request before the managers of the Royal Institution that they would set on foot a subscription for the purchase of a large voltaic battery of cells, as invented not many years previously by Volta, for the production of the electric current. The result was that a battery of 2,000 cells comprising copper and zinc plates in acidulated water was set up, and one of Davy's earliest experiments with it was the production on a large scale of the electric arc.

It is probable that Davy had produced the arc discharge on a small scale in 1802, and according to Quetelet, Curtet had also observed it in that year

In his book *Elements of Chemical Philosophy*, Vol. IV, Davy thus describes his production of the electric arc with the above-mentioned 2,000-cell primary battery. He attached to the terminal wires of the battery two pieces of hard charcoal which had been heated and plunged into mercury to make them better conductors. These charcoal pieces were 1 in. long and about one-sixth of an inch in diameter. When the charcoal rods had their ends brought within about one-thirtieth of an inch from each other a bright spark leaped across the interval and the charcoal pieces became white hot whilst an electric discharge took place over the gap, and when the charcoal rods were withdrawn so that the gap was 4 in. a brilliant arch of light sprung between them. Hence it was called the electric

Digitized by Google

arc. Davy found that in the heat of this arc most refractory substances melted and evaporated.

Many years later, in 1843, J. B. L. Foucault suggested as arc electrodes the use of pencils cut from the hard graphitic form of carbon or coke which is left in coal gas retorts, and he invented also a self-regulating form of arc lamp in which the graphite or coke rods were held in line vertically over each other. The mechanism first caused the proximate ends of the carbons to touch and then separate a little. The carbons were supplied with current by a battery of 50 Grove's or Bunsen's cells. The act of separating the carbons so as to cause the electric-arc to spring between their ends was called "striking the arc."

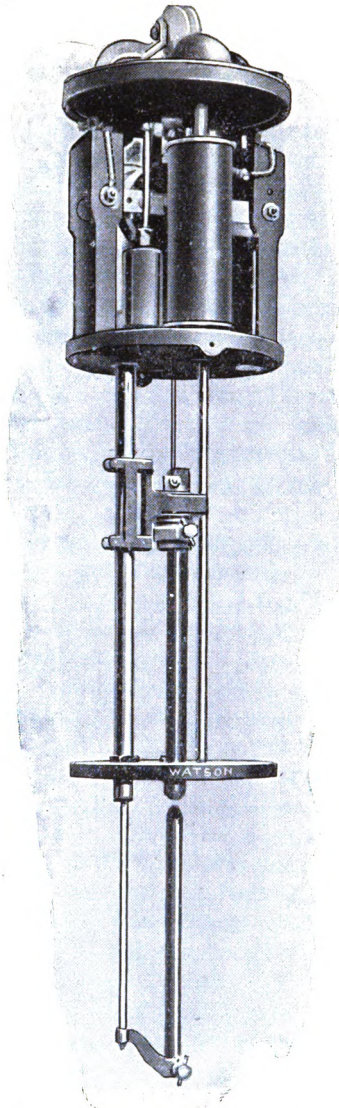
Many forms of self-regulating arc lamps have since been invented which are for the most part operated by electromagnets. (*See* Fig. 1.)

The mechanism of the lamp then kept the carbons at the proper distance apart, but brought them together again and re-struck the arc if the current was interrupted. This Foucault arc-lamp and Grove's primary battery were in use for many years in scientific laboratories and lecture rooms. It was not until the magneto-electric machine and dynamo were invented and perfected that there was any industrial use of the electric arc.

In 1846 W. Greener and W. E. Staite patented a process for manufacturing carbon rods for the arc light, but it was not until after the invention of the Gramme dynamo in 1870 that any great demand for them arose. In 1876, Carré, in France, began to manufacture such carbon rods from finely-powdered coke, lampblack and syrup, which were then intimately mixed, squeezed through a die, and baked in a furnace.

At one time, when electric-arc lighting was largely adopted for public lighting, the manufacture of round arc-light carbons was a great industry. The carbon rods now used

Digitized by Google



By courtesy of Messrs. Watson & Sons.

FIG. 1.—A Self-regulating Arc Lamp for Forming an Electric Arc between Two Hard Carbon Rod Electrodes.

Digitized by Google

for searchlights and electric-arc lamps generally are made by mixing soot or lampblack prepared from burning paraffin residues with syrup and forcing this paste through a die by hydraulic pressure. The soft rods so formed are dried, baked, and intensely heated on a furnace. In some cases the carbon paste is mixed with fluorides of calcium or other metals to give a yellowish colour to the electric light.

2. **The Phenomena of the Arc Discharge.** The physical phenomena of the arc are much the same whatever the materials used for the electrodes, but may best be studied by forming an electric-arc between the ends of two carbon rods made as above described.

If these carbon rods are held in a hand-regulated arc lamp which permits them to be approached to each other whilst kept in line, and if these carbons are connected to a source of electromotive force of low internal resistance, which means one capable of supplying a relatively large current of many amperes at a voltage, say, of 100 volts, we can then observe the following phenomena.

If the ends of the carbon rods are brought near to each other, even if only separated by one-hundredth of an inch in air at normal pressure, and if the potential difference of the carbons is below the voltage corresponding to that sparking distance, no electric-arc will form. If the voltage is greater than corresponds to the sparking distance for the small air gap then a spark will pass, but the spark discharge will be instantly converted into an arc discharge. The characteristic of this arc discharge is that the electrons and positive ions, the movement of which in opposite directions in the interspace constitutes the arc current, come chiefly from the electrodes themselves.

In order that the arc-form of discharge may continue it is necessary that the negative electrode should be kept incandescent. If it is cooled or allowed to cool the arc stops. Another essential condition is that the source of electromotive force should have a small resistance so as to be able

Digitized by Google

to supply the current required. By the term small is here meant a resistance of a few ohms, say, 1 to 20 or so.

The phenomena taking place in the electric arc can best be studied by forming the arc discharge in air between two hard carbon electrodes, the gap between which is kept constant. We can conveniently project an image of the arc upon a white screen by means of an achromatic lens.

We then notice that the positive carbon after a short time is hollowed out into a crater-like form and is intensely incandescent, 85 per cent of all the light emitted comes from the crater. (*See* Fig. 2.) On looking carefully we see certain extra brilliant spots on the crater which are always moving about unless the arc is very short.

The negative carbon becomes incandescent at the tip, but not so hot as the crater end of the other positive carbon. About 15 per cent of the light of the arc comes from the incandescent end of the negative carbon. In 1879 Rossetti estimated that the temperature of the crater of the positive carbon is 3,200° C. and that of the end of the negative 2,500° C.

Violle gave 3,600° C. as the temperature of the crater. The most refractory metals are melted or volatilized in the crater of the carbon electric arc.

Between the incandescent carbons there is a flame, generally of a violet colour. In a steady arc this violet flame appears to spring from the crater, whilst a well-marked dark space separates this purple portion from the golden, wing-shaped flames which originate in the negative carbon. There is probably in the arc a double transport of material, matter from the negative carbon passing to the positive and vice versa. If the electric-arc is lengthened by drawing the carbons apart the aureole of golden flame increases, and at a certain arc-length is extinguished. We then notice that the tip of the positive or crater carbon remains hottest longest. This tip is always converted into graphite after the arc has been burning some time, and

Digitized by Google

then acquires the property of marking paper like a so-called *lead* pencil. One interesting fact with regard to the carbon

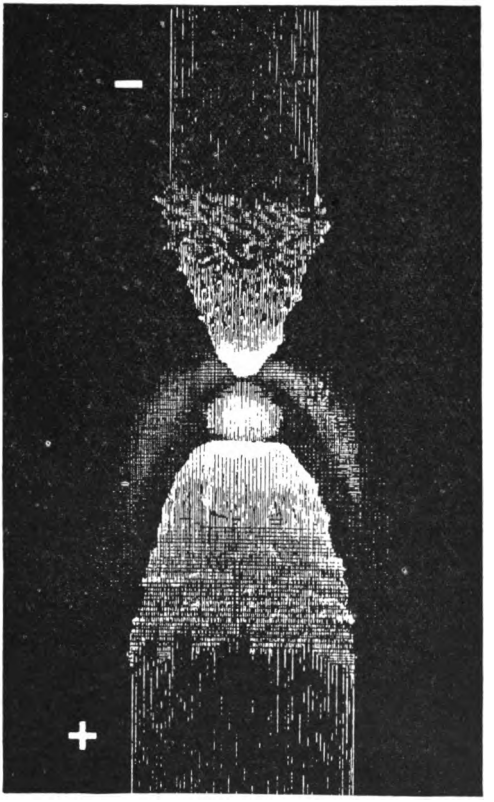


FIG. 2.—An Illustration showing the Appearance of the Electric-Arc between Two Carbon Rod Electrodes when Formed with a Direct Electric Current. The Tip of the Positive (+) Carbon is Hollowed Out into a Crater.

electric-arc is that if the current is increased beyond a certain strength the arc begins to emit a hissing sound.

In the case of the carbon arc in air this hissing is

Digitized by Google

accompanied by a sudden fall of about 10 volts in the potential difference of the carbons.

Broadly speaking, we may say that in the arc-form of discharge the electric current is carried by electrons and positive ions which are not merely formed out of the air molecules, but chiefly out of the vapour produced from the incandescent electrodes. Thus in the carbon arc there is carbon vapour between the incandescent electrode, and this is highly dissociated into carbon ions and electrons. There is a stream of electrons proceeding from the negative carbon, and an oppositely moving stream of carbon positive ions.

In order that the arc may be started, the electrodes must be made incandescent and begin to evaporate. This is achieved by bringing the ends of the electrodes or carbon rods into contact and passing the electric current. The high resistance at the point of contact then generates heat and brings the tips of the electrodes to a temperature at which they begin to evaporate.

The free negative electrons in the negative electrode then have a great velocity imparted to them, and some of them are projected from the incandescent negative electrode just as they are projected from the incandescent metal wire filament in a thermionic valve.

The electric field between the electrodes then draws these electrons violently towards the positive electrode, and on their way they ionize the carbon vapour. The positive carbon ions so produced are attracted to the negative electrode and bombard it, and so keep up its temperature. The electrons which make their way to the positive carbon form a sort of electron cloud round it, and this creates a very sudden fall in potential near the positive electrode, and the resulting large electric force pulls the positive carbon ions out of the incandescent crater, and, in fact, excavates the crater.

This emission of electrons from the negative carbon is

Digitized by Google

supported by a fact discovered by the author in 1889. If a third carbon electrode has its end just dipped into the incandescent carbon vapour forming the true arc, and if this third carbon is connected with the positive carbon by a wire in which is included the circuit of an electric bell or galvanometer we find that a current of negative electricity is flowing from the third carbon through this wire to the positive carbon. (*See* Fig. 3.) If, however, we connect the third carbon with the negative arc carbon we find no current in the wire. The third carbon is, in fact, brought down to the potential of the negative arc carbon. A torrent of electrons proceeds from the incandescent negative electrode. If we insert as above a third carbon into the arc flame, which carbon is connected to the positive electrode, then some of these electrons are deflected towards it and establish the by-pass current above mentioned.

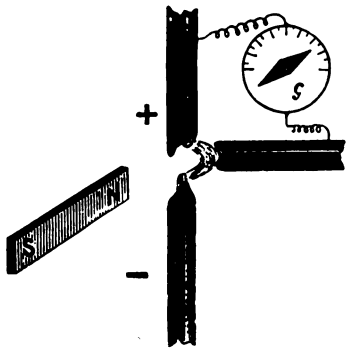


FIG. 3.—An Electric-arc Formed between Two Carbon Rod Electrodes (+ and −) and the Arc Directed by a Magnet N.S. against a Third Carbon Rod.

It has been shown that for steadily-burning electric-arcs between electrodes of various materials that the potential difference V in volts of these electrodes is connected with the length l in millimetres of the arc or gap between the electrodes in a linear relation.

$$V = m + nl$$

where m and n are constants. For an electric-arc in air at normal pressure between solid carbon electrodes the value of m is about 39 volts, and has lesser values for various

Digitized by Google

metals in proportion as the melting point of the electrodes is lower. For mercury the value of m is 12·8 volts.

3. **The Characteristic Curve of the Arc.** The peculiar characteristic of the electric-arc as a conductor is that an increase in the current through the arc is accompanied by a decrease in the potential difference of the electrodes.

Curves, the ordinates of which are proportional to this

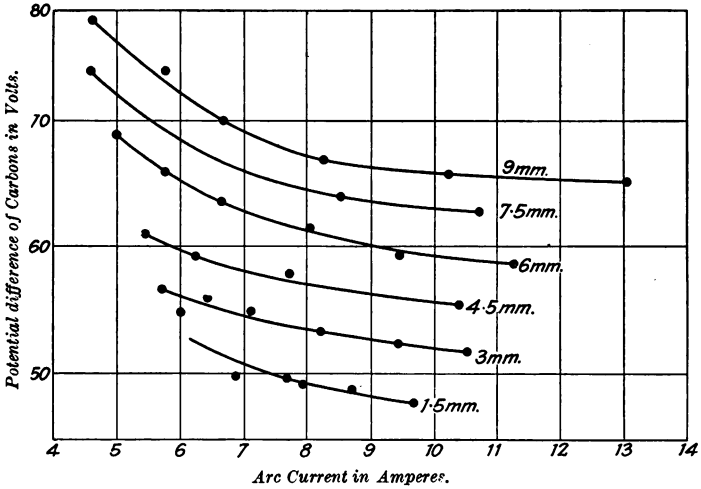


FIG. 4.—The Volt Ampere Characteristic Curves of a Carbon Electric-arc for Various Lengths of Arc.

potential difference, the corresponding abscissae of which denote the arc current, are called *characteristic curves* of the arc. (*See* Fig. 4.)

There are different characteristic curves for each particular length of arc, and for electrodes of various materials and in atmospheres of different gases or vapours. These, in general, are curves which slope downwards and are called descending characteristic curves. It will be seen, therefore, that as a conductor the incandescent carbon or

Digitized by Google

metallic vapour, which constitutes the true electric-arc, differs in an important respect from a solid metallic conductor.

In this last-named type of conductor the potential difference of two points on the conductor increases proportionately to the current flowing between them. This is a statement of Ohm's Law, obeyed by metallic conductors when correction is made for changes of temperature of the conductor. But this law is not obeyed by gaseous or vaporous conductors.

It is sometimes stated that the electric-arc has a *negative resistance*. But this is a rather misleading use of words. Electric resistance is essentially a positive quantity because it is the quality of the conductor in virtue of which energy is dissipated as heat when a current flows through it. A true negative resistance would therefore only exist if the conductor became colder when a current flowed through it, and no instance is known of such an effect taking place in a uniform conducting material.

The correct statement is that the rate of change of arc electrode potential difference with respect to arc current is negative, or that the characteristic curve has a downward slope.

It is on this fact that the application of the electric-arc to produce high-frequency electric oscillations depends.

Our main purpose in this little book is not to discuss the phenomena of the electric-arc in general, but of the mercury electrode arc particularly, and to this we shall therefore devote the next chapter.

Digitized by Google

CHAPTER III

THE MERCURY-ARC LAMP

1. **The Arc Between Mercury Electrodes.** If a vessel full of liquid mercury is connected to the negative terminal of a storage battery of 20 or 30 cells and the other terminal provided with an iron or carbon electrode, and if this latter is brought down to touch the mercury and then slightly raised from it, an electric-arc will form between the mercury and the iron electrode as in the case of two carbon electrodes.

The experiment, however, is inadvisable and unpractical, because the mercury would become heated and volatilized, and mercury vapour is extremely poisonous to inhale. Mercury (Chemical symbol *Hg*) is a metal which is liquid at ordinary temperatures. It is the most dense or heaviest liquid known to us. Its density is 13·596 compared with water taken as unity at 4° C. Iron and other metals therefore float as easily on mercury as a cork does on water. Mercury freezes at – 38·8° C. to a silver-like solid of density 14·19. It boils at 357° C., forming a colourless vapour. When heated in air it is converted into red oxide of mercury.

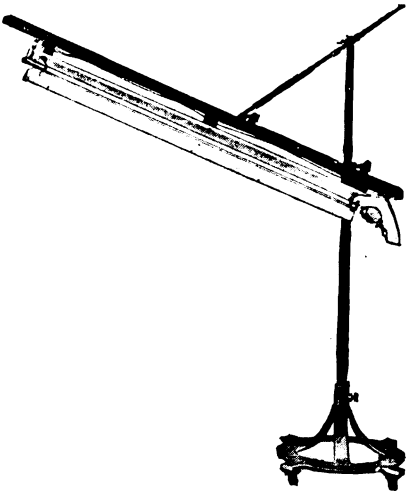
Hence an electric-arc formed between mercury and iron or carbon in air is of no practical use. It was discovered, however, in 1900 by Mr. Peter Cooper Hewitt of New York, that in a high vacuum and in an enclosed transparent vessel or tube the mercury-arc has many valuable properties and uses.[1]

A mercury-arc lamp was therefore invented by him consisting of a long glass tube having a platinum wire sealed through one end. This closed end of the tube con-

[1] The fundamental British patent specification of Mr. Peter Cooper-Hewitt is No. 11,562 of 26th June, 1900, for improvements relating to electric lamps. This specification was amended by disclaimer on 12th February, 1907. The corresponding United States patents are numbered Nos. 682,690, 682,692, 682,694, and 687,882.

Digitized by Google

tains a small quantity (a few cubic centimetres) of liquid mercury, and the platinum wire serves to establish electric contact between the mercury and a source of electric current. The other end of the tube is closed, and a platinum wire ending in an iron or graphite electrode is sealed



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 5.—Cooper Hewitt Mercury Vapour Lamp Hand Tilting 1,200 c.p.

through the glass, or else the tube can have a similar mercury pool to that at the first-mentioned end. To keep these pools of mercury separate the tube is generally bent down at one or both ends. (*See* Fig. 5.) The tube must also be highly exhausted of its air.

Under these conditions it contains only mercury vapour at ordinary temperatures. It would require an electromotive force of several hundred or perhaps thousands of volts to start a glow discharge or electric-arc between these two mercury electrodes if kept at a distance from each other and kept cold.

Digitized by Google

If the tube is tilted skilfully so as to make some of the mercury flow along the tube and make a metallic connection between the two pools of mercury, or between the iron or carbon electrode and the mercury cathode pool, and if an electromotive force of 50 to 100 volts direct current is at the same time maintained between the electrodes, then the current runs along the liquid mercury column. If the tube is then tilted back so as to sever this column and allow the mercury to run back both ways into the one or two separate electrode pools again, an electric arc forms in the vacuous tube between the two separating portions of mercury and the tube fills with a brilliant greenish-white light which is an electric-arc discharge in mercury vapour. It is necessary to maintain, generally speaking, a wire resistance in the circuit outside the tube to prevent the current from increasing beyond a certain strength of a few amperes.

When the arc discharge is established in the tube we see on the surface of that mercury pool which is connected to the negative terminal of the supply, called the mercury cathode, a brilliant spot of light which rapidly darts hither and thither over the surface of the mercury pool and is never still for an instant. The other positive pole or anode appears to be wrapped in a steady glow of light. The peculiar property of this mercury-arc is that it will not persist unless the cathode or negative pole or electrode is a mercury pool, and this mercury cathode must be kept hot or " alive " or else the arc light is at once extinguished.

The mercury cathode has to supply the continual stream of mercury vapour which is to be ionized, and it must therefore be kept at a temperature above the boiling point of mercury in the vacuum used.

It is not necessary that the anode or positive electrode should be a mercury pool. It can be an iron or hard carbon or graphite terminal attached to the platinum wire which is sealed through the glass. The cathode, however, must be mercury.

Digitized by Google

The process which takes place in the tube on forming the arc is as follows—

When the liquid mercury column breaks on tilting the tube back, heat is produced at the point of rupture and mercury is volatilized. This vapour is then ionized by the potential difference of the electrodes, and electrons are projected from the cathode. The positive mercury ions which are produced in the mercury vapour are drawn back with great velocity to the mercury cathode and heat it at one or more places, and this evaporates more mercury and provides more vapour for ionization and more electrons. This ionization of the mercury atoms proceeds all along the tube, and the result of the ionization and de-ionization of the mercury atoms is to produce radiation as explained in the first chapter.

The mercury atom is a large or bulky atom of great mass. The atomic weight of mercury is 200·6, oxygen being taken as 16. The atomic number of mercury is 80. This implies, as explained in Chapter I, that there are 80 planetary electrons revolving round the nucleus in the mercury atom, and that there are nearly 200 protons in the nucleus but also nearly 120 electrons holding the protons together.

Since the atomic weight of mercury is not an integer number there are several isotopes, two or perhaps more, and ordinary chemically pure mercury is a mixture of these various isotopes, having the same atomic number but slightly different atomic weights.

The mercury nucleus is therefore a relatively big bulky mass compared with the atom of hydrogen. One or more of the planetary electrons in the outer orbits are easily removed, leaving a positive mercury ion or positively charged mercury atom *minus* one or more electrons. Hence, when this heavy ion bombards the cathode it sets the atoms and free electrons in it vibrating, and keeps up the cathode temperature and the continual liberation of

Digitized by Google

electrons from the mercury cathode which is necessary to maintain the arc discharge.

The whole space between the mercury cathode and the anode is filled with mercury vapour in a state of ionization, and therefore contains free electrons and mercury ions. The electrons are continually working their way towards the anode, which may be an iron rod. At the anode they are taken up by the positive ions in that anode, and this increases the density or number of free electrons in it.

This excess of electrons then gradually diffuses through the circuit and finds its way round to the cathode through the external circuit. Thus we have the electric current in that circuit formed.

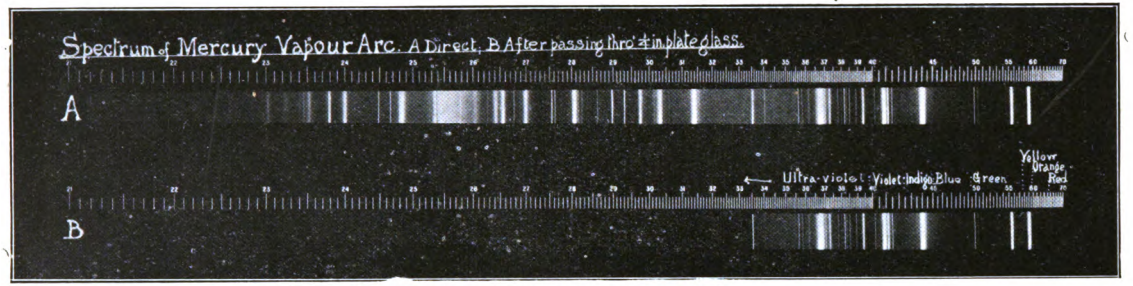
The continual ionization and de-ionization of the mercury atoms creates radiation of certain rays, as previously explained, when electrons fall back into the orbits of ionized mercury atoms.

If we examine with a spectroscope the spectrum of the visible light emitted by the mercury-arc we find it consists of a certain number of bright lines. (*See* Fig. 6.)

If the tube containing the mercury vapour is a glass tube, then nearly all the radiations beyond the violet end of the spectrum are cut off. If the tube is a quartz tube, then, since quartz is transparent to ultra-violet radiations, we can photograph lines in the spectrum far beyond the limits of the visible spectrum, provided that the spectrum has been formed by means of a spectroscope constructed with prisms and lenses of quartz.

The visible light from the mercury-vapour arc consist of radiations given by certain yellow, green, and violet lines, and the discharge in vacuo has a greenish-white appearance as a whole. In the absence of all other sources of light, that is in a dark room, all coloured objects, when viewed by the mercury arc light, present quite a different appearance to that which they do in daylight. The human face,

Digitized by Google



By courtesy of Messrs. Siebe, Gorman & Co.

FIG. 6.—Bright Line Spectrum of Incandescent Mercury Vapour. A in a Quartz Tube. B in a Glass Tube.

Digitized by Google

for instance, assumes an unpleasant corpse-like aspect which is not attractive.

The illustration in Fig. 6 shows the visible and ultra-violet spectrum of the mercury-arc in glass and in quartz tubes. A is the visible and photographic spectrum of the mercury-arc in a tube of fused quartz, and the richness of the ultra-violet spectrum is well shown down to wave-length 2,000 A.U. B shows the spectrum in a tube of a certain glass, which passes ultra-violet radiation down to the wave-length 3,020 Angstrom units (= A.U.). In consequence of this, the mercury-arc in quartz tubes has great photographic utility, and also very great therapeutic or medical value in the cure of certain diseases of the skin.

2. **The Cooper Hewitt Mercury-vapour Arc Lamp.** The mercury-vapour arc discharge produces light from electric energy with a comparatively high efficiency measured in candle-power per watt of electrical power.

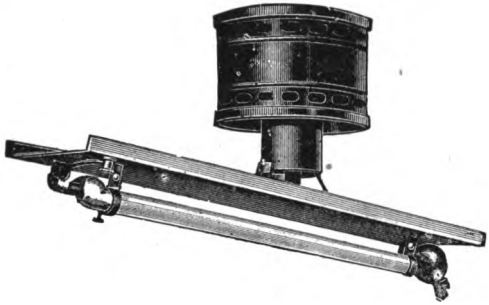
Its uses in this respect as a source of illumination were investigated and discovered by Mr. Peter Cooper Hewitt of New York, as already mentioned, in 1900. This mercury vapour lamp is made in several different forms by the Hewittic Electric Company, Ltd., of England. The simplest type comprises a lead glass tube about an inch or two in diameter and from 27 to 57 in. in length over all. (*See* Fig. 5.)

The tube has at one end a mercury pool contained in a slight enlargement of the tube and at the other an iron anode. Connections are made by platinum wire sealed through the glass. The tube is held in a holder in a slightly inclined position so that the mercury remains at one end. The tube is highly exhausted of its air.

The arc is started by tilting the tube by means of a chain fixed to one end so that the mercury runs up to the anode and the column of mercury conducts the current. On releasing the chain the tube falls back into the inclined position, thus starting the arc, and the tube fills at once with a brilliant glow of light.

Digitized by Google

In another type of lamp the tilting is effected automatically by an electro-magnet as soon as the switch is closed in the supply circuit, and the exciting current of the magnet



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 7.—Cooper Hewitt Mercury Vapour Lamp.
500 c.p. Automatic Tilting.

is cut off as soon as the main arc starts in the tube. (Fig. 7.) These lamps have a long life. There is no waste of any

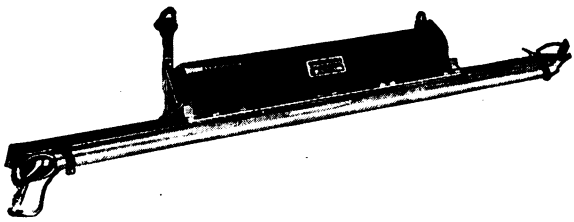


FIG. 8.—Cooper Hewitt Mercury Vapour Lamp.
1,200 c.p. Static Starting.

kind, as the mercury vapour condensed on the walls of the tube trickles back to the mercury cathode pool.

In the case of large lamps a difficulty arises with the automatic tilting type in that the size of the electro-magnet becomes unwieldy for the larger tubes, owing to the mobile mass of mercury it has to control. To eliminate this

Digitized by Google

difficulty a further type of lamp of considerable interest is made which employs the glow discharge to ionize the small quantity of mercury vapour residual in the tube at normal temperatures, and so establish the mercury arc.

The design of this tube is similar to that of the ordinary pattern, except that the outside of the cathode bulb is coated with a metallic paint forming a condenser with the mercury, the dielectric being the glass wall of the bulb.

An additional circuit is made by connecting the cathode electrode to the anode through a resistance, which limits the current to 1 ampere, and in the same circuit a choking coil of high inductance is connected. This circuit passes through a quick " make and break " mercury switch, known as the " shifter," consisting of a small glass bulb exhausted of air, indented on one side and containing a small quantity of mercury. The indentation divides the shifter into two receptacles, each provided with a glass and platinum seal which connects it into the circuit. In the normal position the mercury bridges these two connections, so that a small current passes through the induction coil. By rotating the shifter the indentation cleaves the mercury into two pools with a quick break, when an arc is immediately established, as in the tilting type of tube. Owing to the low current and the rapid cooling of the mercury vapour, brought about by the comparatively large volume of the shifter, this arc is immediately interrupted.

As a result of this rupture of a highly inductive circuit, a large potential difference is created at two points, namely, between the anode and the cathode by way of the tube, and between the two plates of the condenser formed by the metallic paint on the outside and the mercury on the inside of the cathode bulb. This potential difference, which runs into several thousand volts, is insufficient to rupture the glass wall of the cathode bulb, but at normal temperatures ionizes the small amount of free mercury vapour in the tube and produces a glow discharge, which

Digitized by Google

is immediately changed into an arc, on account of the resulting cumulative volatilization of the mercury.

Fig. 8 shows the general appearance of a 48 in. ($3\frac{1}{2}$ amperes at 100 volt) 1,200 c.p. lamp operating on this principle, the automatic movement of the shifter being effected by the induction coil which, when the tube strikes up, holds the armature of the shifter in the " break " position, and interrupts the shifter circuit.

The operation of the Cooper Hewitt lamp on direct current only has been dealt with so far, and for this reason. If a tube provided with one main anode and a mercury cathode is connected to an alternating current supply, the current when the arc is struck will try to flow alternately from the iron to the mercury and vice versa, corresponding to each half wave of the supply. This means that the cathode is alternately iron and mercury. Assuming that iron is a suitable metal to operate as a cathode, which it is not, as will be seen later, the temperature of the cathode at the spot where the arc strikes is kept sufficiently high to obtain emission of electrons only during one half-cycle, and consequently at the point where the wave passes the zero potential line, that is, at the instant when the arc is passing from one direction to the other, it is extinguished. The A.C. Cooper Hewitt lamp is provided, therefore, with a transformer and a tube with two main anodes, as shown in Fig. 14, and operates in exactly the same way as the single-phase rectifier, which is dealt with in the next chapter.

Due to manufacturing difficulties, these lamps are not made in the " tilting " type, but are started up by means of a shifter as described above, only one of the anodes being connected to the metallic coating on the cathode bulb.

In the Cooper Hewitt lamp the efficiency measured as watts consumed is approximately 0·25 watt per candle, but on account of the series resistance only 70 per cent of the actual current consumed is utilized in the tube itself, giving a true efficiency of 0·35 watt per candle.

Digitized by Google

The light is absolutely steady, and as it proceeds from a large surface, say a considerable fraction of a square foot, there is none of the detriment to vision or the dazzle which takes place with the incandescent filament lamp in which the light proceeds from a source of small surface at a very high temperature.

The sole disadvantage is the colour of the light, which unfits it for use where discrimination of true colour difference is essential, but this is perfectly unobjectionable for much factory, workshop, or industrial lighting. These lamps are made for various candle-power (500 to 1,200 c.p.), and for the ordinary standard electric supply voltages, 50 to 250 volts. Each lamp takes 3·5 amperes to work it.

The luminous efficiency of the glass tube lamp is about 3 c.p. per watt of electric power expended in it. These lamps must, of course, be worked with direct current, as they will not operate unless the mercury is the cathode or negative electrode. The 50-volt lamps may be worked two in series off 100-volt supply, or four in series off 200-volt supply.

The tubes can be made of any diameter from $\frac{1}{8}$ in. to 3 in., and of any reasonable length to give candle-power from 16 to many thousands of candle-power, and to take current from 0·2 to 20 amperes and to work on D.C. voltages of 50 to 500 volts.

The light is extremely steady and proceeds from the whole of the surface of the tube. Although of a whitish-green colour, the light is soothing in character, and in many respects less trying to the eyes than a light in which the red and yellow rays predominate.

In the absence of fracture of the tube there is no necessary wear and tear or consumption of material to shorten the " life " of the lamp.

In the case of the glass tube lamp there is a limit to the current density which can be employed, and therefore to the luminous efficiency, which is imposed by the necessity of not allowing the glass tube to rise above a certain

Digitized by Google

temperature or else it would crack. A great improvement, therefore, was effected by the introduction of a mercury-vapour arc lamp with a fused silica tube.

Owing to its extremely small coefficient of expansion with heat, silica does not crack like glass when heated and cooled quickly, or when unequally heated, and as it has a

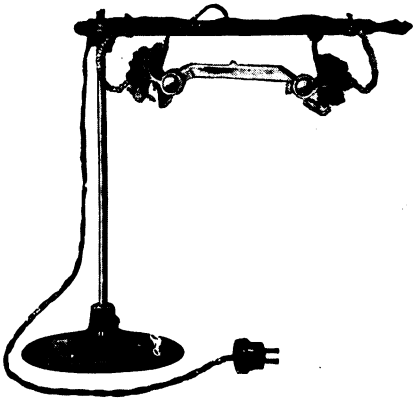


FIG. 9.—A 220-volt Mercury Vapour Arc Lamp for General Laboratory Purposes.

far higher softening temperature than glass it can be used at a much higher temperature.

The development as a commercial industry of the manufacture of tubes, bulbs, and vessels of transparent fused silica which do not crack when strongly heated, has made it possible to make a very great improvement in the efficiency of the mercury-vapour lamp by working it at a greater current density and therefore at a higher temperature.

The luminous efficiency of the silica tube mercury-arc lamps is about 5 c.p. per watt or 0·22 watt per candle-power. The lamp then consists of a fused silica tube provided with two mercury electrodes, one at each end. The tube is very highly exhausted and sealed up. This tube is called

Digitized by Google

the burner. The average life of a silica burner is 4,000 hours, as made by the Hewittic Electric Company of England.

In use, the burner is held in a holder connected to an

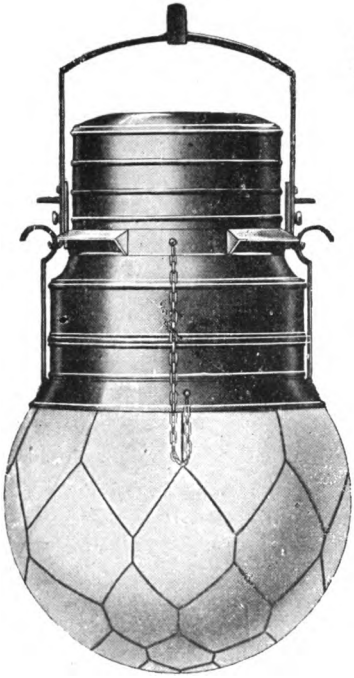


FIG. 10.—3,000 c.p. Mercury Vapour Lamp in Silica Tube and Enclosing Lantern.

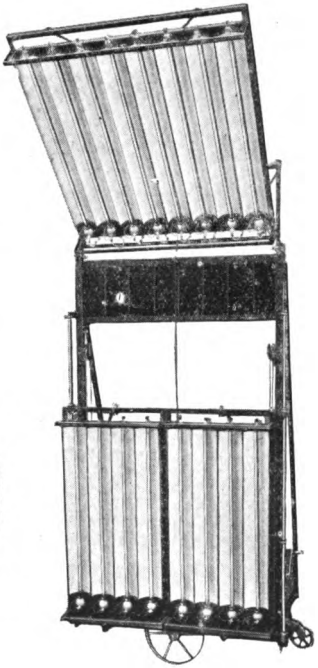


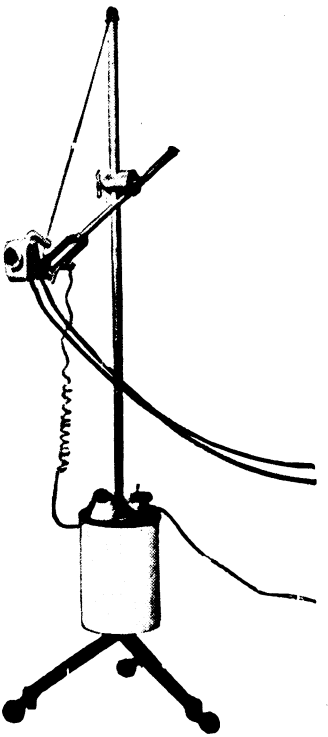
FIG. 11.—Banks of Mercury Vapour Arc Tubes for Photographic Work. 10,000 to 80,000 c.p.

electro-magnet tilting or starting mechanism. The whole arrangement is contained in a lantern with a netted globe of glass (*see* Fig. 10) so that the whole of the light is thrown downwards and well diffused. Owing to the higher temperature of working, the light is of a rather whiter colour than in the case of the glass tube mercury lamp.

Digitized by Google

Each lamp is independent of all the rest. The lamps work off the supply circuit in parallel, and light up instantly on closing the associated switch.

3. **Some applications of the Mercury-vapour Lamp.** Owing to the richness of the light in ultra-violet rays the Cooper Hewitt Mercury-vapour lamps have an extensive use in connection with photography, for printing blue prints or copies from engineers' or architects' tracings, and for making prints from photographic negatives, for enlargements, and for photographic studio and portrait work in dull weather, or for making lantern slides these lamps have a wide field of usefulness.



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 12.—The "Kromayer" Mercury-vapour Arc Lamp in Silica Tube, with Water Cooling Arrangement for Medical Purposes.

Banks of tubes can be arranged so as to give a very extended radiating surface, and as a consequence harsh shadows can be prevented and a very close approximation to the diffused light of daylight obtained. (*See* Fig. 11.) Hence these lamps have many applications in the equipment of moving picture studios.

Another very important application, especially of the

Digitized by Google

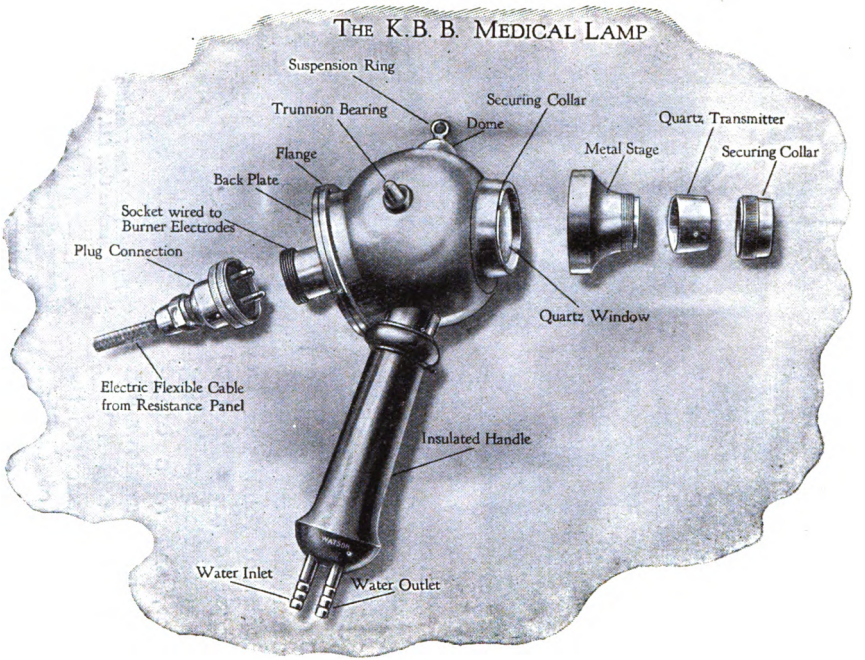
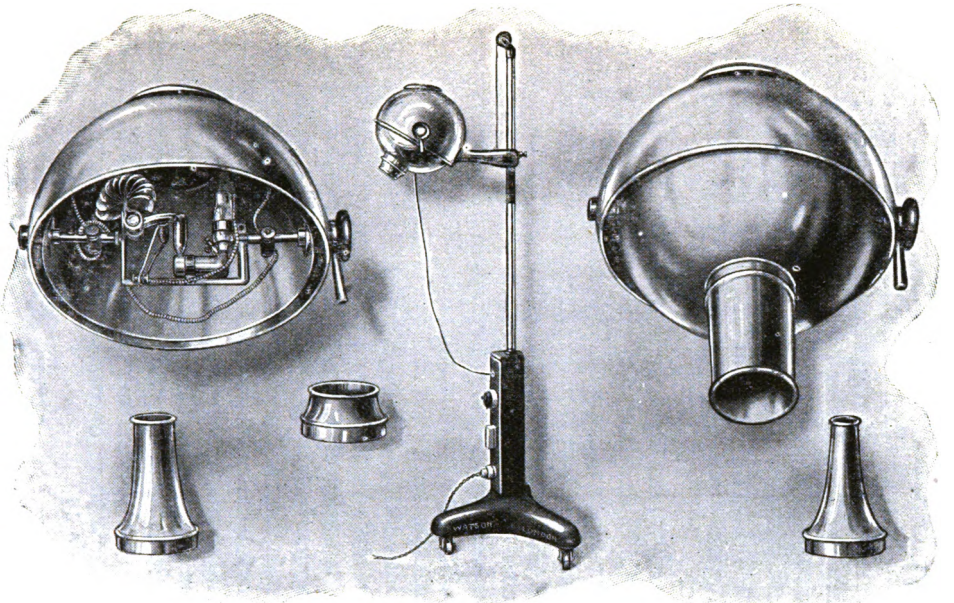


FIG. 13.

Digitized by Google



By courtesy of Messrs. Watson & Sons.

FIG. 13a.—Details of the K.B.B. Mercury-vapour Medical Lamp for Producing Ultra-violet Radiation. The Lamp comprises a Mercury-vapour Arc Lamp in a Silica Tube in a Water-cooled Chamber.

Digitized by Google

silica lamp, is in ultra-violet radiotherapy. The beneficial effect of ultra-violet radiation on many human diseases has been known for some time, and many devices have been employed for generating the required rays. The Finsen Arc Lamp using carbon electrodes was at one time much used. After that the arc between iron electrodes in a quartz vessel filled with compressed air or other gas. Following this came the Kromayer Mercury-vapour Arc provided with a water-cooling arrangement to cut off heat rays.

A mercury-vapour arc lamp in a silica tube, as made by the Hewittic Electric Company, is a convenient source of strong ultra-violet radiation. This is fitted into a double envelope of transparent quartz in which water circulates so as to stop off all calorific rays and pass the ultra-violet light required. (*See* Fig. 12.)

It has been found that the ray in the mercury-arc spectrum, having a wave-length of 2536·7 A.U., is remarkable in exciting resonance and for producing therapeutic or remedial effects. The rays useful for this purpose lie beyond the wave-length 2,500 A.U. In Figs. 13 and 13a are shown the details of a similar device, called a K.B.B. mercury-vapour lamp, made by Messrs. Watson & Sons. This also comprises a mercury-vapour arc in a quartz tube, which is enclosed in a water-cooled metal jacket. The ultra-violet light is emitted through a quartz window and can be radiated on to any part of the patient's body as required.

4. **Chemical Transformations in the Mercury-vapour Lamp.** It is a very extraordinary thing that in certain mercury lamps there appears to be a transformation of mercury into gold.

Whilst engaged on certain experiments two German chemists, Professor Miethe and Dr. H. Stammreich, found that certain mercury-vapour lamps when in use for some time become "aged," the inside of the glass bulb being covered with a dark deposit, and the question of the nature

Digitized by Google

of this deposit came into question. After careful analysis of it the discovery was made that it undoubtedly contained small quantities of pure gold.

A special apparatus was made in which the mercury vapour was produced from perfectly pure mercury, but was raised in the lamp to a very high temperature.

The current was passed at a voltage of 170 volts for several hundred hours, and the result of all tests was to procure an exceedingly small quantity, less than one-tenth of a milligramme of pure gold.

If we remember that the atomic number of mercury is 80 and that of gold is 79, and that the atomic weight of mercury is 200·6, whilst that of gold is 197·2, we see that the atom of mercury needs but a small modification, viz. a loss of 1 unit of atomic number and 3·4 units of atomic weight to be changed to gold.

From the non-integer value of these atomic weights we see that there are most probably isotopes both of mercury and gold (*see* Chapter I), and that if so the loss of one electron and three protons from the mercury atom might suffice to transform it to the gold atom. That electron would not come from the planetary electrons, at least not from an outer ring, and the protons must come from the nucleus. Hence the minute transformation of mercury to gold which seems to have taken place must have been a break-up of the nucleus of the mercury atom such as happens on a much more pronounced scale in the case of the transformations of Uranium, Thorium, and Radium, called the radio-active elements. These are all characterized by high atomic weight and a certain instability in the bulky atomic nucleus.

Digitized by Google

CHAPTER IV

THE MERCURY-ARC RECTIFIER

1. **The Unilateral Conductivity of the Mercury-arc Discharge.** It has been mentioned in the previous chapter that for an electric arc to be formed in vacuo between a mercury and an iron or graphite electrode the current supplied must be direct current, and the mercury electrode must be the negative pole or cathode of the tube or bulb.

It was noticed at an early stage in the investigation of the subject by Mr. Cooper Hewitt that when an alternating current is used with such a discharge tube as above-mentioned, the current only passes in the mercury vapour during one-half of the time, namely, during that phase of the current in which the mercury pool is the negative electrode and the iron or carbon the positive electrode. Hence the mercury-vapour arc discharge in vacuo has a unilateral conductivity, or exerts a valve action upon the alternating current. This is essentially dependent upon the different nature and temperature of the two electrodes.

In order that an electrode may act as a cathode or negative pole it must emit electrons, and it can only do this if it is kept at a high temperature.

It is the same with the incandescent tungsten filament in the thermionic or Fleming valve, which when raised to a high temperature in vacuo emits electrons in virtue of the fact that at a high temperature the kinetic energy of the free electrons in the metal is increased to a point such that some of them are projected through the surface of the metal into the vacuous space outside.

In the thermionic valve the function of the filament current is to keep up the temperature of the cathode, and we do this by supplying power from the filament-heating battery.

Digitized by Google

In the arc discharge the temperature of the cathode is kept up by bombardment with positive ions which come from the vapour between the electrodes. Mercury has especial advantages as a cathode. In the first place it has a high atomic weight, nearly 200, and therefore a low specific heat, and in the next place it has a relatively low boiling point and small latent heat of vaporization. Lastly, the mercury atom has a very large family of planetary electrons, and it easily loses one or more of them, or has a low ionization potential. Finally, the mercury atom nucleus has a large mass relatively to other atoms. All these qualities make for its exceptional utility as a cathode.

When once electrons have been emitted from a mercury surface, either by heating it strongly as in " striking the arc " in a mercury-vapour lamp, or by the momentary application of a very high negative E.M.F., then the emitted electrons ionize the mercury vapour immediately formed, and the subsequent bombardment by the heavy or massive positive mercury ions keeps up the temperature of some spot on the mercury surface to the electron-emitting temperature.

On the other hand, an iron electrode has no such good cathode power, but very useful properties as an anode. Iron is very infusible and therefore non-volatile. It has a relatively high specific heat and is a rather good conductor of heat, so that local heating to a high temperature is not easily effected.

Hence, if a vacuous tube is provided with a mercury electrode at one end and an iron electrode at the other, we can easily start an arc discharge in the tube by tilting it, provided we use a direct current and make the mercury electrode the negative one.

We cannot, however, start the arc discharge in such a tube if the mercury is made the positive electrode, because the iron will not act as a cathode unless heated to a very high temperature.

Digitized by Google

Hence, if we use an alternating current supply it is more difficult to start the arc in such a tube, and even if started only one phase of the current passes through the tube, viz. that which makes the mercury electrode the negative one and the iron the positive.

2. **The Single-phase Mercury Rectifier.** We can utilize both phases of an alternating current provided we employ

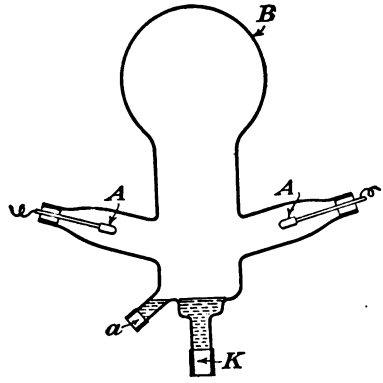


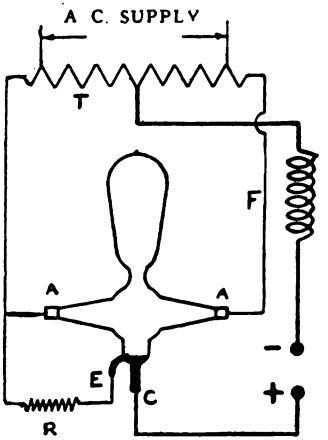
FIG. 14.—Cooper Hewitt Single-phase Mercury-vapour Rectifier in Glass Bulb.

a slightly different form of tube called a single-phase mercury rectifier. This tube (*see* Fig. 14) has two iron or graphite electrodes and one mercury cathode pool.

The tube is generally made in the form of a pear-shaped bulb, the mercury cathode K being at the small bottom end of the bulb. A little way up there are two lateral extensions of the bulb AA, called the anode arms, and at the ends of these are sealed in platinum wires carrying the two graphite anodes. Also there is a supplementary mercury pool at *a*, near the main cathode K, which is called the starting electrode. Let us then suppose we have a supply of alternating current at a commercial frequency 16, 25, 50, or 100, and that it is supplied from the secondary circuit

Digitized by Google

of an alternating current transformer at a voltage, say, of 50 or 100 volts. This secondary circuit must have its middle point connected through an inductance coil F with an insulated terminal marked — in Fig. 15. The corresponding terminal marked + is connected to the main



By courtesy of the Hewittic Electric Company, Ltd.

FIG. 15.—Scheme of Circuits for Rectification by Mercury-vapour Rectifier of a Single-phase Alternating Current.

mercury cathode C. The two anodes AA are connected to the outer ends of the transformer secondary circuit. There is also a connection from one end of the secondary circuit through a resistance R to the starting electrode E.

The bulb is highly exhausted, and the function of the bulbous part is to condense the mercury vapour and cause it to trickle back as liquid to the main cathode pool C.

If, then, we turn on the supply of alternating current and give the bulb a tilt so as to cause the mercury in the pools C and E to be connected for a moment and then separated, an alternating current arc starts between the two mercury electrodes E and C. This volatilizes mercury and fills

Digitized by Google

the space in the vessel with ionized mercury vapour. When this takes place current begins to flow from the alternating current supply, and the two anodes AA come into operation alternately. When, say, the right-hand end of the transformer secondary becomes positive, then the current flows to the right-hand iron anode and through the mercury vapour to the cathode C. When the left-hand of the transformer circuit is positive then the current flows from the left-hand anode A to the cathode C.

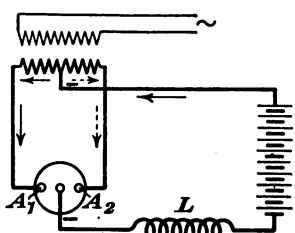


FIG. 16.—Scheme of Circuits for Storage Battery Charging by a Single-phase Mercury Rectifier.

A_1 A_2 are the Anodes of the Rectifier and L an Induction Coil.

In order that this current may flow, some appliance capable of conducting current must be connected to the terminals + and —. It will be seen, then, that the current from the cathode C through the above-mentioned appliance and the inductance coil F is always in the same direction. Accordingly, the appliance connected to the terminals + and — may be one which must be operated or actuated by a direct current such as a direct-current motor or a storage battery to be charged (*see* Fig. 16) or another D.C. mercury lamp with mercury-iron electrodes. In other words, the alternating current supply given by the transformer T to the two anodes AA comes out as a direct current supply from the terminals + and —. (*See* Fig. 15.)

Digitized by Google

This conversion is called the rectification of a single-phase alternating current and the apparatus is called a mercury-vapour rectifier. When once the arc discharge between the electrodes AA and C is fairly started it is not necessary to keep the starting mercury electrode E going. A switch between E and R may be opened to cut out the electrode E. The object of the resistance R (*see* Fig. 15) is to limit the arc current which flows between E and C at starting down to 2 or 3 amperes at most, which is enough to heat the mercury pool C and make it "alive" as a cathode.

The inductance coil F must be inserted in the circuit of the main cathode C for the following reason. The alternating E.M.F. of the transformer, and therefore its current, falls to zero between the reversals of direction, and hence at that instant the cathode C would have no voltage and would become dead. If we insert in the circuit a large inductance coil F its inductance makes the current in it run on after the E.M.F. has fallen to zero, and this keeps the main cathode alive until the alternating E.M.F. has begun to increase again and can maintain the arc discharge through the mercury vapour. The above is the arrangement in its simplest form of a mercury rectifier for single-phase alternating current.

Quantitative Theory of the Single-phase Mercury Rectifier

Since the electro-motive force in the transformer secondary circuit varies in a periodic manner it is approximately represented by the ordinates of a sine curve or by a function of the time, $e = E \text{ Sin } \omega t$, where $\omega = 2\pi$ times the frequency n, e is the instantaneous E.M.F. and E its maximum value. It follows that the rectified E.M.F. is not absolutely steady, but is a pulsating current and has a certain mean value. If the curve 1 in Fig. 17 represents by its ordinates the fluctuating or alternating E.M.F. in

Digitized by Google

the transformer secondary circuit, then the curve 2 in Fig. 17 represents the rectified E.M.F., and the mean value of this last is denoted by the height of the dotted horizontal line above the firm base line or line of zero E.M.F.

An ordinary hot wire or electrostatic voltmeter applied to the transformer terminals will give the root-mean-square or R.M.S. value of the potential difference or

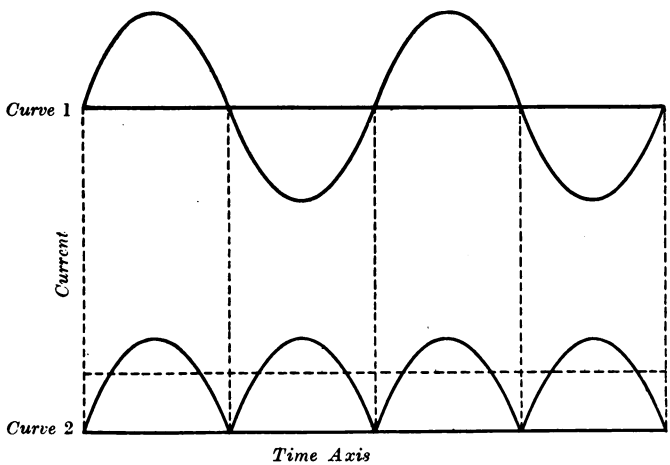


FIG. 17.—The Curve 1 represents by its Ordinates the Variation of Current in a Single-phase Alternating Current, and the Ordinates of Curve 2 the Current when Rectified by a Single-phase Rectifier. The Current is then direct but Pulsating.

E.M.F. in the secondary circuit. If V is the total R.M.S. voltage at the ends of the secondary circuit, then since only one-half of the secondary is supplying current or voltage at a time, we have $V/2$ as the applied alternating E.M.F.

The rectified E.M.F., as read by a direct current voltmeter, would be the true mean value of the alternating E.M.F. during one half-period.

In the case of an alternating current or voltage the ratio

Digitized by Google

of the R.M.S. value to the true mean (T.M.) value was named by the author the *Form Factor* (f) of the curve or T.M. = (R.M.S.)/f.

For a simple sine curve-variation the form factor is $f = 1{\cdot}11 = \frac{\pi}{2\sqrt{2}}$. There is, however, in the mercury rectifier a certain nearly constant drop in voltage necessary to maintain the arc, which is approximately 15 volts. Hence the effective or available direct voltage which may be denoted by V_d together with the 15 volts in the arc is the mean value of half the total R.M.S. value of the transformer secondary voltage V or

$$V = 2{\cdot}22\ (V_d + 15)$$

If the connection of the mercury cathode is to the geometrical middle point of the secondary circuit, then since the current supplied by the transformer passes only through one half of the transformer coil at a time, it makes a volt-drop in it due to resistance, and the actual available alternating voltage for rectification is a little less than $V/2$. Accordingly, the resultant mean direct voltage V_d available at the terminals + and — is better represented by the formula

$$V = 2{\cdot}37\ (V_d + 15)$$

$$\text{or } V_d = \frac{V}{2{\cdot}37} - 15.$$

For many technical purposes there is an objection to employing a pulsating direct current. The pulsations can, however, be reduced and the current smoothed out by inserting in the path of the direct current supply a large inductance, and connecting across the terminals + and — of the D.C. supply a large condenser which acts as an electrical reservoir and keeps the D.C. current steady.

3. **The Three-phase Mercury Rectifier.** A considerable part of the alternating current supply from public or

Digitized by Google

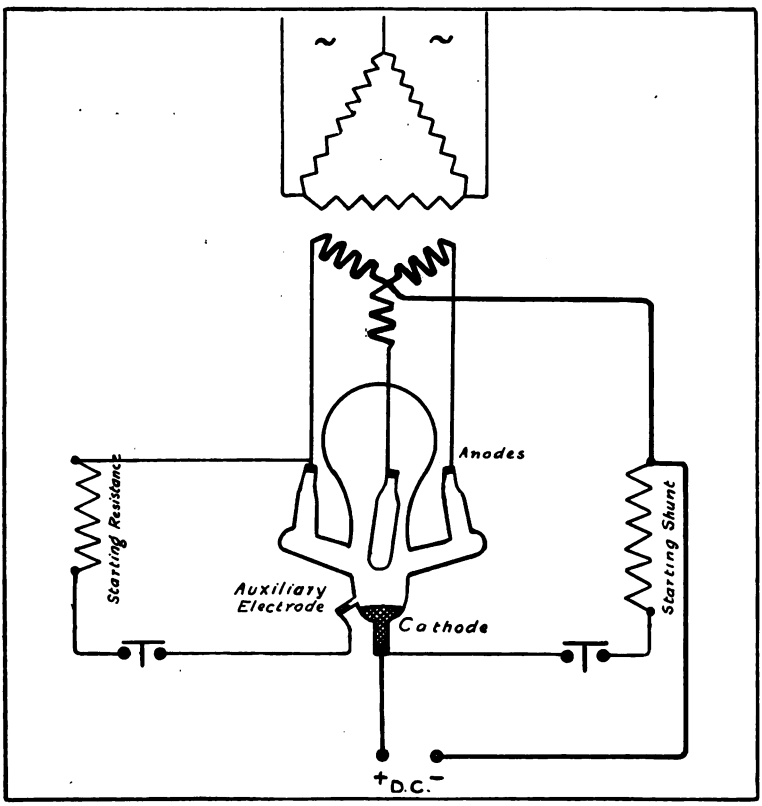


FIG. 18.—Connections for a Three-phase Rectifier by the Hewittic Electric Company's Glass Bulb Three-phase Mercury-vapour Rectifier.

Digitized by Google

private electric supply stations is in the form of three-phase current, and this requires a somewhat different form of mercury rectifier. In this case the mercury bulb has three graphite anodes and one mercury cathode. The

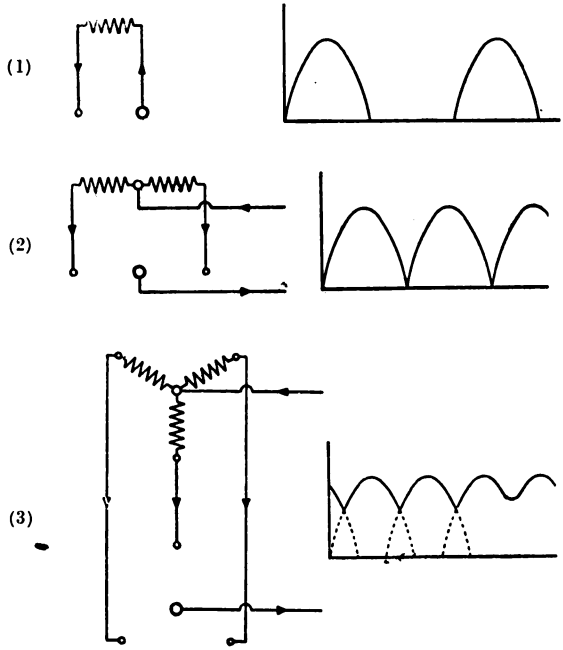


FIG. 19.—Diagrams illustrating the Rectification of an Alternating Current and the Resulting Pulsating Current.
(1) Single-phase, One-phase Rectified.
(2) Single-phase, both Phases Rectified.
(3) Three-phase, all Phases Rectified.

transformer secondary circuit which supplies the A.C. voltage must be star connected, and the mercury cathode is connected through the appliance to which direct current is to be furnished, to the central point and the three anodes to the ends of the star arms. (*See* Fig. 18.)

The D.C. terminals are in the circuit leading from the

Digitized by Google

midpoint of the transformer to the mercury cathode. The mode of operation of the three-phase rectifier is exactly the same as in the single-phase rectifier, only each star-arm of the transformer and each anode of the mercury rectifier comes into operation successively. Since there is 120° phase difference between the three alternating E.M.Fs, the curves representing them overlap, and hence the rectified current never quite falls to zero, but is subject to pulsations which are not so marked as in the case of the single-phase rectification.

This is shown by the curves in Fig. 19, which demonstrates that owing to the overlapping of the three-current waves the rectified currents consist of a steady part with a superimposed fluctuating or periodic part. Hence the rectification of a three-phase alternating current gives us a less pulsatory direct current than does a single-phase alternating current.

We can carry this process a step further and employ what is equivalent to a six-phase or hexaphase current necessitating six anodes in the bulb and one mercury cathode. (*See* Fig. 20 (1).) In the case of glass bulb rectifiers it is more convenient to employ two separate three-anode bulbs in parallel, operating from the six terminals of the hexaphase transformer, on account of the manufacturing difficulties of making six-anode glass bulb rectifiers.

If we have a star-connected secondary circuit in our three-phase transformer we can consider each star-arm to be the secondary circuit of a single-phase transformer, and we can connect its two ends to two anodes and its middle point to the mercury cathode. We can do this for each of the three star-arms and make use of a rectifier with six anodes, the pair belonging to each star-arm secondary being placed at opposite sides of the bulb or mercury-vapour container. (*See* Fig. 21.) We cannot very well multiply the anodes beyond six, because there is

Digitized by Google

then great risk of short-circuiting and starting discharges between adjacent anodes

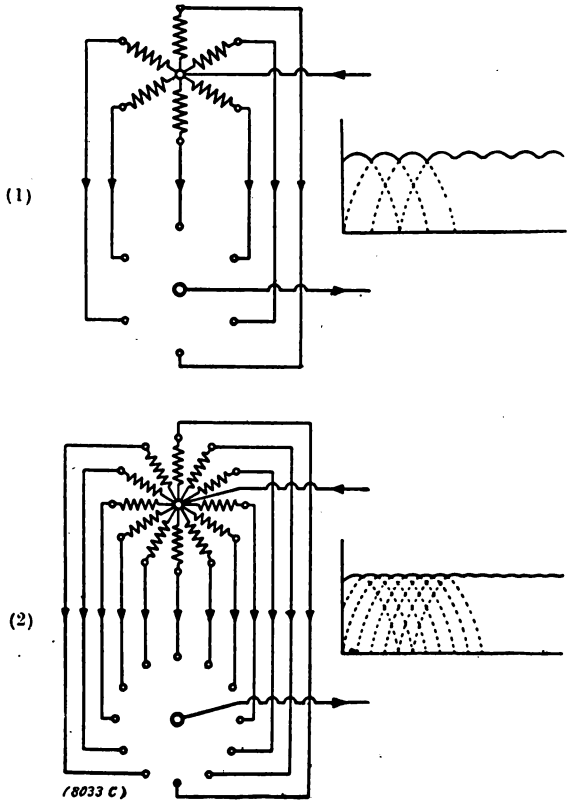


FIG. 20.—Diagram illustrating the Rectification of a Six-phase (1) and Twelve-phase (2) Alternating Current.

The six-anode rectifier with three-phase currents is very largely employed, and the result is to give a rectified direct current which has less fluctuations in it than the three-anode rectifier current. (*See* Fig. 19 (3) and 20 (1).

Digitized by Google

If the bulb or mercury-vapour vessel is made of glass, then it is most usually a three-anode rectifier. The three

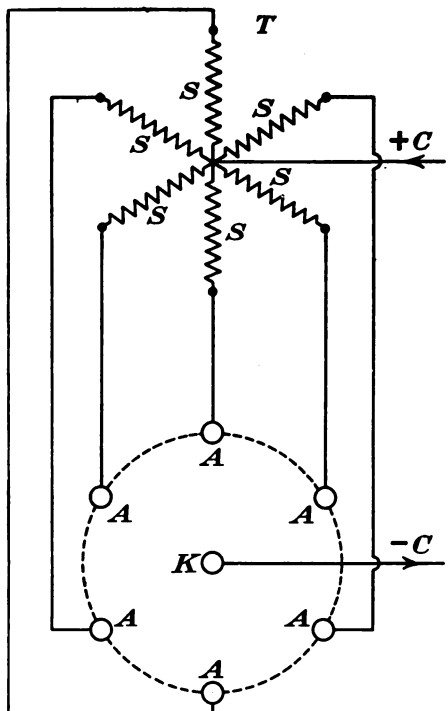


FIG. 21.—Scheme of Connections in Case of a Six-anode Mercury Rectifier Rectifying Three-phase Alternating Current.

S, S are the Secondary Currents of the Transformer T. A, A are the Anodes and K the Mercury Cathode of the Rectifier, and the Direct Current is delivered at the terminals—C and C.

graphite anodes are placed in tubular projections sealed into the bulbs which are at angles of 120°.

If we consider a three-phase rectifier with three anodes, each connected to the ends of a star-arm secondary circuit

Digitized by Google

of a three-phase transformer, the neutral or middle point being connected to the mercury cathode, then we can calculate as follows the ratio of the direct-current voltage (V_d) in the rectified or cathode circuit to the three-phase line voltage (V_a) as follows—

Let V_a be the root mean square (R.M.S.) value of the potential difference between the outer ends of the star-arms of the secondary circuit or otherwise the voltage read by a suitable voltmeter across each phase of the line. (*See* Fig. 18.)

Then $V_a/\sqrt{3}$ is the R.M.S. value of the voltage in each star-arm. The maximum value of that voltage, if we assume a sine wave form, is $V_a\sqrt{2}/\sqrt{3}$. Let this be denoted by V. Then if we draw the three partly overlapping voltage curves for the three star-arms, as in Fig. 19 (3), we see that the available rectified voltage V_d, together with the voltage dropped in the mercury arc, which is about 15 volts, and together with the resistance drop in voltage in the star-arm must be the mean value of the voltage in each star-arm. Call this last M and let us neglect first the resistance drop in the star-arm. Then since the phase difference of the three star-arm voltages is $120° = T/3$ where T is the periodic time taken for the complete cycle, we have

$$MT/3 = V\int_{30°}^{150°} \sin \omega t \, . \, dt$$

where $\omega = 2\pi/T$.

The value of the definite integral is $-\frac{1}{\omega}\cos \omega t$, and the value of it, taken between the limits $\omega t = 150°$ and $30°$ is $\sqrt{3}/\omega$.

Hence we have

$$\frac{MT}{3} = \frac{V_a\sqrt{2}}{\sqrt{3}} \frac{\sqrt{3}T}{2\pi}$$

$$\text{and } M = V_d + 15$$

Digitized by Google

$$\text{Therefore} \quad V_a = \frac{\pi\sqrt{2}}{3}(V_d + 15)$$

$$= 1{\cdot}8\,(V_d + 15).$$

In this we have neglected the resistance drop in the star arm. If we take this into account the relation between V_a and V_d is better expressed by the formula

$$V_a = 1{\cdot}6\ V_d + 28.$$

4. **The Efficiency of the Mercury-vapour Rectifier.** —Having seen that the mercury-vapour arc is a convenient and practical rectifier of alternating current or means of converting alternating current, whether single-phase or polyphase, into direct electric current, the important question arises of the efficiency (η) of the device, or percentage of power applied to the bulb in the form of alternating current which comes out of it in the form of direct or rectified current.

This proves to be very high and more uniform with varying load than is the case with mechanical rectifiers such as the rotary converter or three-phase induction motor coupled to a direct-current generator or dynamo. The reason for this is the approximate constancy at all loads of the voltage dropped in the converter itself. We have seen that at the cathode there is a drop of about 15 volts, and this is nearly independent of the current.

This volt drop corresponds to the work done at the cathode in vaporizing the mercury and in drawing through the surface the electrons necessary to the maintenance of the arc. The true efficiency of the rectifier can only be ascertained by the employment of a suitable dynamometer wattmeter.

The power supplied to the rectifier in the form of alternating current is measured by the product of the R.M.S. values of the current and of the potential difference of the terminals and the power factor of the appliance.

Digitized by Google

The power factor is not exactly unity for the mercury-vapour arc. It may have values between 0·9 and 0·95. This means that the current may lag behind the impressed E.M.F. in phase by 25° to 18°.

Hence we can only measure the power given to the rectifier by means of a properly calibrated wattmeter.

In the same manner the output of the rectifier is not a perfectly uniform direct current, but a pulsatory current which is approximately represented by a sine form alternating current superimposed on a direct current, and expressed by such a formula as

$$I_c + I \sin (\omega t + \alpha)$$

where I_c is the direct part and I the maximum value of the alternating part and $\omega = 2\pi n$, where n is the frequency of the pulsation and α is a phase difference. Also the rectified voltage is expressed by the formula

$$V_c + V \sin \omega t$$

and, accordingly, the power given to the external circuit by this rectified current is given by

$$W_d = \frac{I}{T} \int_o^T (I_c + I \sin (\omega t + \alpha) (V_c + V \sin \omega t) \, dt$$

$$= I_c V_c + \frac{IV}{2} \cos \alpha$$

where T is the periodic time.

Thus, for a certain mercury rectifier supplying incandescent lamps, it was found that the current A was given by

$$A = 6{\cdot}9 + 2{\cdot}9 \sin \omega t$$

and the voltage E by

$$E = 103 + 42 \sin \omega t$$

Since the drop in voltage in the rectifier is nearly independent of the rectified voltage, it follows that the

Digitized by Google

efficiency η increases with the D.C. voltage ; and also that the efficiency remains high and nearly the same over a

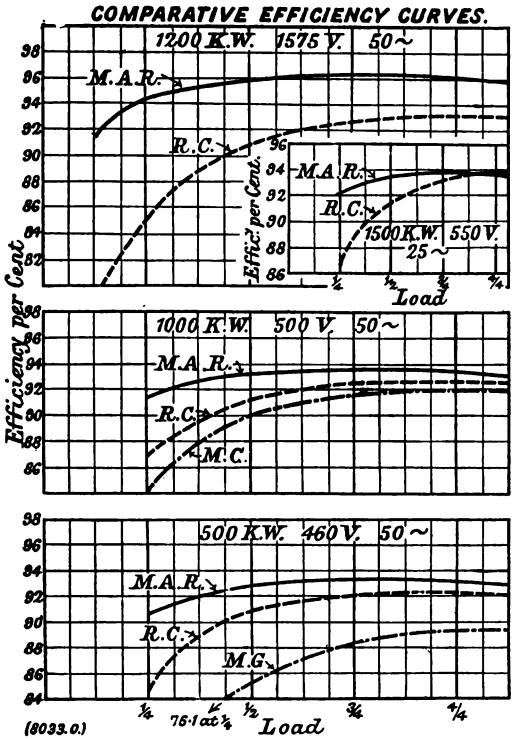


FIG. 22.—Curves showing the Comparative Efficiencies at Various Fractions of Full Load of the Brown, Boveri All-metal Mercury-arc Rectifiers (M.A.R.), and a Rotary Converter (R.C.) and Motor Generator (M.G.) of the same Power for Sizes to 1,200, 1,000, and 500 Kilowatt Output at a Frequency of 50 Cycles.

large range of load from full load to much less than half load.

It is this high and nearly constant efficiency over varying loads that is the most valuable quality of the mercury

Digitized by Google

rectifier, and gives it a considerable advantage over forms of mechanical rectifier or combinations of A.C. motor and D.C. generator, the efficiency of transformation of which fall off very greatly at low loads. The curves given in Fig. 22 show the efficiency of a certain mercury rectifier at various fractions of full load.

It will be seen that it remains above 90 per cent down to quarter load and at full load is 95 per cent. Therefore the mercury-vapour rectifier stands on a level as regards efficiency of transformation of energy with the best dynamos and static transformers. The curves given in Fig. 22 show the relative efficiency of mercury-arc rectifiers (M.A.R.) and motor-generators, or rotary converters (M.G. and R.C.), taken from a paper by Mr. R. L. Morrison, published in *Engineering* of 19th and 26th October, 1923, on Mercury-arc Rectifiers. It will be seen how superior the mercury-arc rectifier (M.A.R.) is at low loads in comparison with the rotary converter (R.C.) in efficiency of conversion.

In concluding this chapter it may be mentioned that the fundamental British patent specification of Mr. Peter Cooper Hewitt for the mercury rectifier is No. 4,168 of 1903, but the date claimed for the patent under the Patents Act, 1901, is 30th October, 1902, for improvements in the method and means for obtaining unidirectional current from a single- or polyphase alternating current source. The corresponding United States patents are Nos. 955,459 and 955,460.

Digitized by Google

CHAPTER V

THE MERCURY-VAPOUR RECTIFIER IN ELECTRICAL ENGINEERING

1. **Types of Rectifier Used in Electrical Engineering.** The discovery of the above-mentioned facts as to the efficiency of a mercury-vapour rectifier soon caused electrical engineers to desire to make use of it in practical engineering.

The greater bulk of all electrical supply is in the form of alternating current, either three-phase or single-phase. The ease with which such current can be raised or lowered in voltage by static transformers and therefore generated at low or moderate pressures, transformed up in voltage for economic transmission over long distances and transformed down again for utilization, make the alternating current a very valuable servant of humanity.

There are, nevertheless, certain purposes for which the direct or unidirectional electric current is essential, such, for instance, as charging storage batteries, for electrolysis or electroplating, for electric traction and arc lamps in picture palace projectors. The direct-current motor has great advantages in traction over the alternating current motor. It is less bulky and less costly per horse-power, and the arrangements necessary for controlling the motor speed are simpler and cheaper than is the case for alternating current motors.

Accordingly there is a considerable demand for direct current for street car traction and for certain electric railway work. Hitherto this has been accomplished by the use of rotary converters, but such a machine consisting of an asynchronous motor coupled to a direct-current generator requires far more continuous attention than a static transformer or even than a mercury-vapour rectifier. Electrical engineers soon, therefore, became very much

Digitized by Google

disposed to give the mercury rectifier an opportunity for test in the case of large scale supply.

Two large firms devoted themselves to its manufacture, one in Great Britain and the other in Switzerland. In Great Britain the Hewittic Electric Company, Limited, of Hersham, Walton-on-Thames, Surrey, England, are manu-

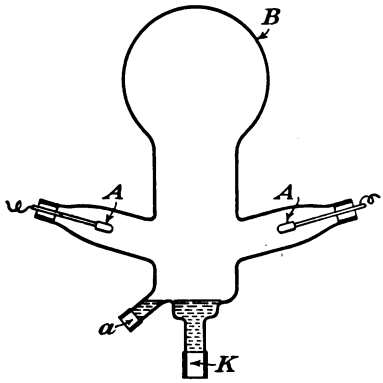


FIG. 23.—Glass Bulb Mercury-vapour Single-phase Rectifier of the Hewittic Electric Company, Ltd.

facturing mercury-vapour plant for large scale rectification, using the glass bulb mercury rectifiers.

In Switzerland, the eminent firm, Messrs. Brown, Boveri & Co., of Baden, near Zurich, have developed on most practical lines the all-metal vessel mercury rectifier for low and high voltage working.

2. **The Hewittic Electric Co.'s Glass Bulb Rectifiers.** The general arrangements for a glass bulb mercury rectifier for single-phase current have already been described. In the simplest type of this rectifier there are two rectifying anodes at the end of horizontal tubular extensions of the pear-shaped bulb and also a third small mercury electrode starting anode. This starting electrode may also be of graphite. (*See* Fig. 23.)

Digitized by Google

One difficulty with the single-phase rectifier which is required to carry a very variable or intermittent load is the maintenance of the requisite temperature of the cathode. The method formerly used was to arrange in parallel with the principle direct current consuming device, whether arc lamp or storage battery, a wire resistance with a throw-over switch, so that when the consuming device was switched off the rectifier was by that act switched over on to a resistance taking perhaps a third of the current of the consuming device. This method, though effectual in keeping the mercury cathode alive, was very wasteful of power, because the rectifier was drawing in at least one-third of the full load power even when the active device (arc lamp, etc.) was not being used.

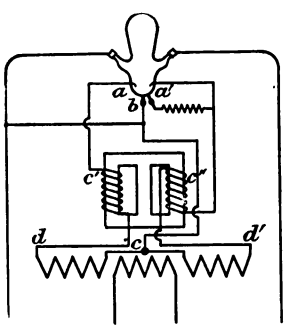


FIG. 24.—The Hewittic Company's Single-phase Mercury-vapour Rectifier, with Double-starting Anodes $a\ a^1$.

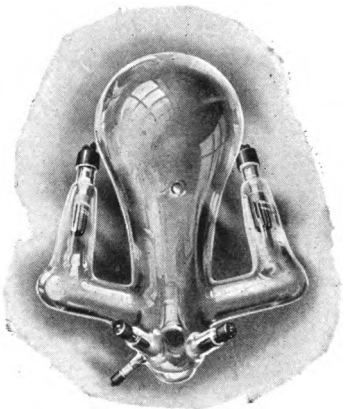
In modern single-phase rectifiers for large power, the Hewittic Electric Co. now make the bulb with two additional small anodes $a\ a^1$. (*See* Fig. 24.) These are connected through two inductance coils $c\ c^1$ with the ends of the transformer secondary circuit, as also are the main anodes. There is also, as usual, a small starting mercury anode which is connected through a resistance coil with one transformer terminal. The general view of this four-anode rectifier bulb, with its mercury cathode and five other anodes designed for 200-ampere rectification, is shown in Fig. 25.

The two small supplementary anodes take only about 200 watts in power to maintain the main mercury cathode alive, and the arc therefore starts to the main anodes as soon as the circuit taking the main direct current is closed.

Digitized by Google

In the practical appliance the bulb is carried in a support which enables it to be tilted to one side on a pivot so as to slop over some mercury from the main cathode to the starting anode, and then tilt it back again as soon as the main arc starts. This tilting is done automatically by an electro-magnet, and takes place the moment that call is made for a rectified current by closing the main switch. As soon as the main arc starts in the bulb this tilting magnet goes out of action and is automatically switched off, and also the circuit to the starting anode is opened.

The bulb has also to be kept cool by a vertical current of air produced by an electric fan, so that the upper part of the bulb is kept cool enough to condense the mercury vapour and allow it to trickle back to the main cathode.



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 25.—View of a Single-phase Hewittic Mercury Rectifier with Glass Bulb, Two Exciting and One Starting Auxiliary Electrodes.

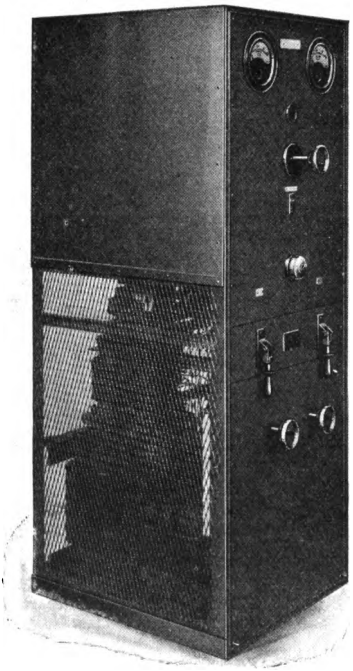
The bulb and all auxiliary apparatus, tilting gear, inductances, and transformer is enclosed in a steel cubicle, the front panel of which carries the switches for closing the A.C. and D.C. circuits and also the ammeters and voltmeters.

There is also a hand-wheel for shifting the contacts on rheostats or travelling terminal connections at the end of the transformer so as to control and vary the A.C. and D.C. voltage.

In Fig. 26 is shown a view of the 100 ampere rectifier of this type. The efficiency of the rectifier increases with

Digitized by Google

the voltage of supply, and, moreover, as the voltage of supply increases the variation of efficiency with change of load decreases. At 220 volts supply the efficiency varies very slightly between quarter load and full load, and may, in fact, be considered as constant from 89 per cent at full to 85 per cent at quarter load. (*See* Fig. 26*a*.)



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 26.—View of the 100 to 150-ampere Hewittic Electric Company's Mercury Rectifier Plant for Three-phase Currents.

The complete 100-ampere unit is not bulky, being only 30 in. wide, about 40 in. deep, and 88 in. high over all. Hence it takes up but little room in places where it is installed to rectify single-phase alternating current supply for projection arc lamps for cinemas or photography or tracing printing. In reckoning out the direct current voltage V_d from the single-phase alternating current voltage V_a we have the rule

$$\frac{V_a}{2{\cdot}37} - 15 = V_d$$

Thus a single-phase 220-volt supply gives us about 78 volts, which is convenient for an arc lamp supply through some resistance. These rectifiers are built to suit all the ordinary commercial frequencies. In the case of small rectifiers for 40 or 30 amperes the tilting of the bulb for

Digitized by Google

Digitized by Google

Digitized by Google

starting the arc is done by hand. The bulb is held in a cradle and a handle on the switchboard permits the starting to be effected. When the arc is started the current to the starting electrode is switched off.

The convenience and economy of these rectifiers is very great when an arc, say, for cinema projection or a lecture slide projection lantern, has to be worked off a 220-volt alternating supply. In fact it is far better to have an alternating current rectified than a direct current from the point of view of economy in power.

Thus, for instance, if a single arc lamp has to be worked off a 220-volt D.C. supply, we know that the arc requires, say, 10 amperes for a small arc and 50 to 60 volts at the arc terminals. We have then to drop no less than 170 volts in a bulky resistance, and this means 170 $\times$ 10 watts lost. If the arc is used only for an hour this means 1·7 Board of Trade units, which at 4d. a unit is nearly 7d. an hour over and above the cost of energy actually necessary.

In the case of an alternating current supply we can drop the necessary volts in a choking coil of variable inductance placed in the primary circuit of the arc transformer, which consumes but little power, and connect the arc lamp of the projector straight into the D.C. terminals of the mercury-vapour rectifier.

In the case of a mercury-vapour rectifier used on a 220- or 110-volt single-phase alternating current supply, the necessary splitting of the voltage required for working the mercury rectifier is accomplished by a single coil or auto-transformer. The coil of this transformer has its ends connected to the terminals of the supply circuit and also to the anodes of the rectifier, and its middle point to the cathode of the latter.

For storage battery charging from urban electric supply, either for traction or wireless work, the small mercury-vapour rectifier has a very useful field of operation when

Digitized by Google

that supply is in the form of alternating electric current, either single- or three-phase.

The mercury-vapour rectifier permits the charging of storage cells to be then conducted at constant current, and if it is necessary the charging voltage can be varied by a variable choking coil placed in the alternating current side which drops volts without much power consumption.

3. **Large Sub-station Rectifiers.** One great advantage of the mercury-vapour rectifier is that a number of the bulbs can be worked in parallel and can divide the load equally between them, provided certain regulations and switching can be carried out simultaneously.

This application has been facilitated by the great increase of current-carrying power for a single bulb effected of late years. Prior to 1914 the maximum capacity of a single bulb was 40 amperes, but the Hewittic Electric Company now manufacture rectifier bulbs which can rectify up to 200 amperes for a single bulb. A number of rectifier panels each containing a single bulb can be arranged to work in parallel, and thus give rectified current for operating a system of street cars for a city from three-phase alternating current supplied from a distant hydro-electric power station.

The present current limit of a single glass bulb is 200 amperes, while the highest D.C. voltage for large power work is 500 to 550 volts, the usual figures for traction supply in this country.

In order to obtain, therefore, sufficient capacity for a 600-kilowatt traction sub-station equipment, eight bulbs would be arranged in parallel, the additional power available being reckoned as an overload rating. The advantages of such an arrangement lie in the fact that, supposing for any reason one bulb, or its auxiliary gear, failed, the whole sub-station would not be put out of action thereby, as the remaining seven bulbs, or whatever number there were, would remain in operation. Further, as the demand for

Digitized by Google

power on the plant increased, additional bulbs could be added gradually to bring up the capacity, without interfering with the existing bulbs.

A typical six-phase glass bulb rectifier installation, transforming three-phase alternating current high tension supply to direct current at 500 volts, consists essentially of—

(*a*) The main step-down transformer, the secondary of which is star connected for six-phase working, and transforms the high-tension supply down to the requisite anode voltage to obtain the specified D.C. pressure. This transformer is usually a separate unit from the rectifier.

(*b*) The rectifying bulb with all its auxiliary apparatus, enclosed in a sheet steel cubicle. (*See* Fig. 27.)

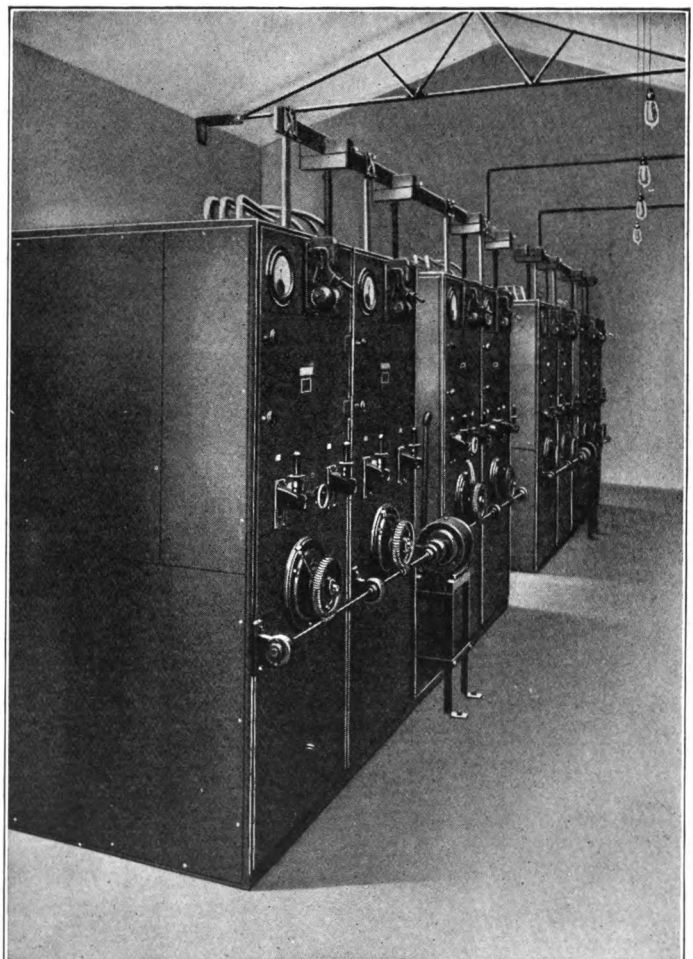
If we follow through the connections on such a rectifier, from the transformer secondary to the D.C. terminals, we find that each cubicle is provided with an amount of auxiliary apparatus.

First of all there is a three-pole A.C. switch usually of the oil immersed type, and employed in conjunction with the D.C. switches, to isolate an individual cubicle from the remainder of the bank.

From here the connections are made to a small star-connected auto-transformer, provided with a number of tappings on each of its three limbs. These taps are provided for varying the anode voltage and consequently the D.C. voltage, and for this purpose are connected to a rheostat fitted with travelling contacts, the movement of which can be effected either by a hand-wheel or motor-driven gearing.

Before taking the supply from this tapping switch to the rectifier-bulb anode arms, it is brought through a three-limb anode inductance, the core of which is adjustable so that the A.C. drop in pressure across the winding can be varied over comparatively narrow limits. The object attained by this is, that when several bulbs are working in parallel, very slight discrepancies in the length of anode

Digitized by Google



By courtesy of the Hewittic Electric Co., Ltd.

Fig. 27.—Bank of Hewittic Rectifiers for 550-kilowatt Fully Automatic Three-wire Light and Power Sub-station.

Digitized by Google

arm, size of condensing chamber or degree of vacuum, will serve to throw an undue proportion of the load on to one or two bulbs, but by adjustment of this choke, equal distribution can be obtained with great accuracy. It will be seen from Fig. 28 that with two cubicles working in hexaphase parallel only one anode inductance is provided for the two units, there being two windings on each limb, one for each corresponding phase in the two cubicles. Space will not permit an explanation of the results of this, other than that much better performance is obtained from an equipment of given size than would otherwise be the case.

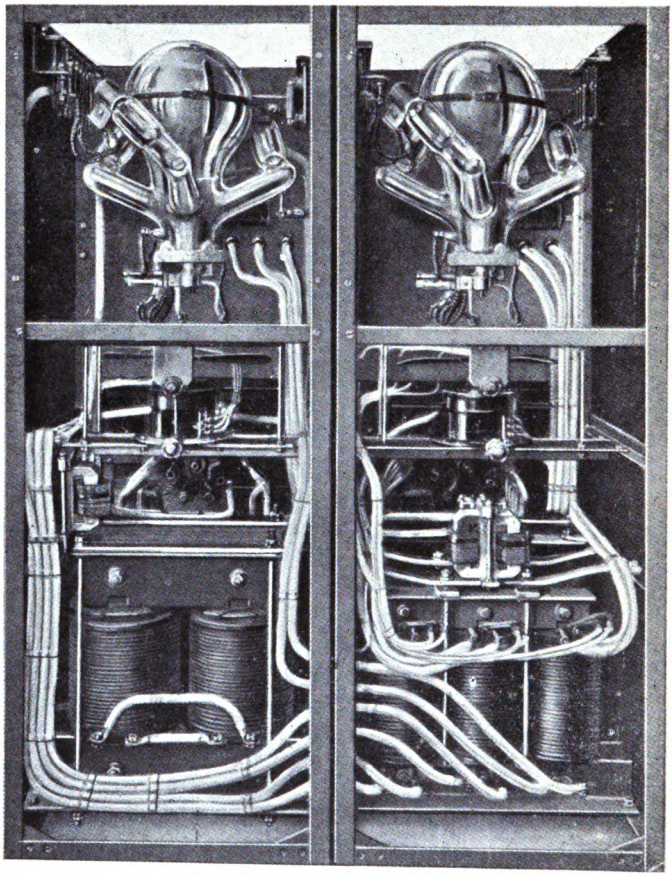
To the rectifier bulb is the next step. Owing to the large diameter of the cathode lead-in bulbs of this capacity, it is divided in half, and two seals are made between the external connections and the mercury cathode.

The rectified current is now brought through a further induction coil, which serves to smooth out the pulsations as in a single-phase rectifier, so that the resultant D.C. waveform differs very little from that of a good dynamo machine.

The next step is through a knife switch, and automatic overload circuit breaker, and so to the D.C. positive busbar. It will be noted that the D.C. negative pole does not enter the cubicle for any of the main connections, as it is formed solely by the star point of the main transformer. Actually a light lead is brought to the star point of the auto-transformer, which serves to damp any slight unbalance of the phases which may occur from cumulative inaccuracies in manufacture of the coils, bulb, etc.

Mention has previously been made of the exciting circuit fitted to single-phase bulbs and also of the automatic starting gear, and the ventilating fan. It is found that on the largest bulbs the voltage on the cathode at the minimum pressure produced by the overlap of the phases, is insufficient to maintain the requisite cathode temperature

Digitized by Google



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 28.—Back View of Two Cubicles, part of a Six-phase Fully Automatic Hewittic Glass Bulb Rectifier Plant.

Digitized by Google

for continuity of the arc, and therefore an exciter circuit is fitted. This consists of an entirely separate single-phase circuit in the same bulb, but operating as a small independent rectifier, the load comprising the drop in its own inductances and in the automatic starting gear.

One limb of the auto-transformer is provided with an auxiliary single-phase insulated winding, giving 120 volts, the mid-point being tapped for the negative pole.

The two extremities are connected through small exciter anode inductances to two subsidiary anodes on the rectifier bulb, placed a short distance above the cathode mercury level.

These exciter anode chokes serve the same purpose as a resistance in the cathode circuit, but provide in addition to a voltage drop of almost the full 120 volts, sufficient inductance to overlap the half-waves and eliminate the zero potential at which the cathode would cease to be alive. The cathode on the bulb is connected through a relay coil, back to the mid-point of the auxiliary single-phase winding.

Two relays are fitted with contacts, one to interrupt the circuit to the tilting electro-magnet, which is operated by the A.C. supply from the auxiliary winding; the other opens the circuit to the starting electrode, both relays operating as soon as the exciter current is passing.

The supply to the ventilating fan-motor, which is of the three-phase squirrel-cage type, is obtained from a further auxiliary winding on all three limbs of the auto-transformer.

It will be seen from the above that it is only necessary to energize the primary side of the main step-down transformer, when the rectifiers are ready after the lapse of a few seconds to take up load, provided all the switches on each individual cubicle are closed, and this is usually the case.

The rectifier thus lends itself to being started up and shut down either from a distance by means of pilots or

Digitized by Google

without any human agency by an automatic relay, connection of the transformer to the electric supply being made by means of an electro-magnetically operated oil-switch. Such a sub-station is illustrated in Fig. 29. In these cases it only remains to obtain automatic control of the D.C. voltage, and this is done by means of a reversible D.C. motor operated from the rectifier busbars, the starting and stopping in either direction being done by means of contactors operated by an adjustable voltage relay set to the required D.C. voltage.

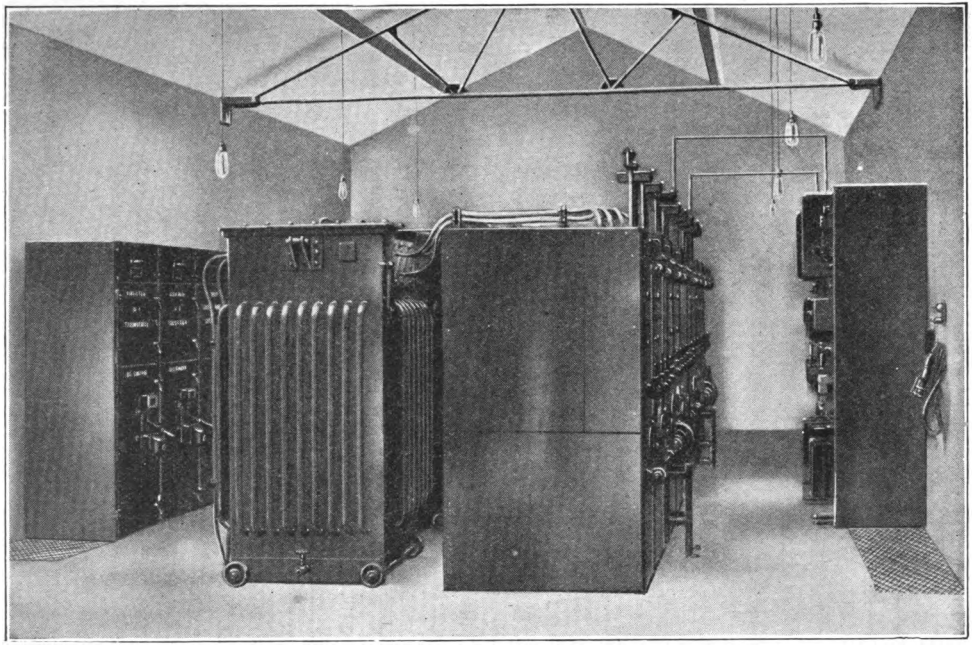
In Fig. 27 is shown a view of the rectifier panels of a bank of Hewittic rectifiers for a 550-kilowatt fully automatic sub-station for such purpose. Fig. 28 shows the back view of a pair of the steel cubicles with six-phase glass bulb rectifiers and the necessary auto-transformer with tapping points and connections.

The ventilating and rectifier starting are all quite automatic and effected at once on closing the main alternating current supply switch. Even the starting and stopping of the rectifier station can be effected from a distant control room by means of remote control switches, provided pilot wires are run back to the control room to inform the operator as to the performance and load on the rectifier.

In Fig. 29 is shown a view of a 550-kilowatt totally automatic sub-station for traction work built by the Hewittic Electric Co., Ltd.

4. **Brown, Boveri Co.'s All-metal Mercury Rectifiers.** In spite of the fact that the glass bulb mercury rectifier has been brought to a condition of great practical utility and durability, many electrical engineers, especially those connected with railway working, have felt some hesitation in equipping large public traction systems with a rectifier involving a fragile glass bulb, especially considering the tendency of glass to fracture by reason of unequal heating and resulting expansion.

Digitized by Google



By courtesy of the Hewittic Electric Co., Ltd.

FIG. 29.—View of a 550-kilowatt Fully Automatic Booster Sub-station Equipped with Glass Bulb Hewittic Mercury-vapour Rectifiers.

Digitized by Google

Accordingly, the eminent Swiss engineering firm, Messrs. Brown, Boveri & Co., of Baden, directed attention some years ago to the problem of abolishing the glass bulb and making a mercury-vapour rectifier with a steel containing-vessel for the vapour. This involved very great difficulties in making the joints and keeping the vacuum high in the interior. For efficient performance it is essential that the vacuum should be kept below 0·001 of a millimetre of air pressure when the arc is not in operation.

It was only after long research and much expensive experiment that the problem was solved completely of making a mercury-vapour rectifier with an all-metal case which could be opened for cleaning and inspection and yet sealed so tightly as to retain the necessary vacuum. The standard type of metal rectifier adopted was one with six anodes rectifying three-phase alternating current and able to rectify high voltages of 5,000 volts and currents up to 1,000 amperes.

A low-tension type of rectifier deals with voltages up to about 600 volts and currents up to 1,000 amperes, and a high-tension type with voltages from 600 up to 3,000 or 5,000 and currents from 750 to 250 amperes according to the voltage.

These units give the power of dealing with the rectification of three-phase currents up to many thousands of kilowatts, since the rectifiers can be worked in parallel, with certain precautions. The first problem which had to be solved was that of making the joint vacuum-tight at the cover of the rectifier and also at the places where the current is led in to the anodes and cathode in the interior.

The rectifier consists of a cast steel cylindrical pot or vessel of carefully selected material. It is made with a flange on which a flat cover fits. Through this cover pass the copper rods which connect to the iron anodes. The joints are made with vulcanized india-rubber and mercury seals at the places where the temperature does not rise high

Digitized by Google

enough to damage the rubber, and with asbestos and mercury seals for joints where there is heat. The diagram in Fig. 30 will show the manner in which the anode rods are taken through the cover, with asbestos washers denoted by *b* and mercury seals denoted by *a*. Mercury seals have the great advantage that if mercury leaks into the vacuum

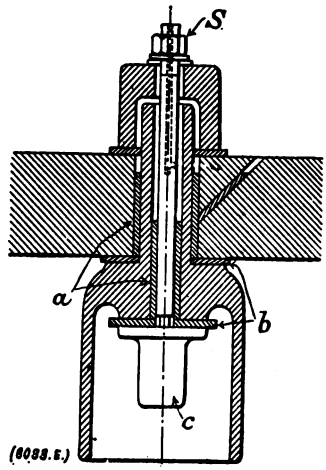


FIG. 30.—Diagram showing the Method of Making the Air-tight Joint with Asbestos and Mercury of the Anode in the Brown, Boveri All-metal Mercury-vapour Rectifier.

under the external air pressure it does no harm to the rectifier.

The cylindrical metal case is jacketed, and a water circulation is provided to cool it. The lid or top carries a tubular extension which is a condensing chamber for mercury vapour. In the low-tension rectifiers this condensing tube is provided with radiator flanges for air-cooling and in the high-tension it is jacketed for water-cooling. The section of the Brown, Boveri high-tension mercury rectifier is shown in Fig. 31, and general views of the

Digitized by Google

low- and of the high-tension rectifiers are shown in Figs. 32 and 33.

One of the greatest difficulties which had to be overcome in working out this hexaphase rectifier was that of preventing arc discharges from starting between the neighbouring anodes inside the vessel.

In the chapter on the theory of the rectifier it was explained that the rectifying power essentially depends upon the difference in temperature of the cathode and anode. The cathode is kept hot by continual bombardment by the positive mercury ions which are drawn towards it. The mercury ion having an atomic weight of nearly 200 is a heavy mass relatively to other atoms. The heated mercury evolves electrons which are shot out of it, and these striking the atoms of mercury vapour continually produce the ions, which in turn keep up the temperature of the cathode. The iron anode, on the other hand, is only bombarded, if at all, by the negative electrons near it which have very small mass, and if it is kept from becoming hot it does not emit electrons. Should it, however, become hot and emit electrons, then, since neighbouring anodes are at different potentials, owing to the manner in which each anode in turn becomes most positive, an arc discharge may start between two anodes and the rectifier " backfires " as it is called. This, however, has been overcome by surrounding the anode with a sort of metal sleeve or tube which is insulated from it. This sleeve is shown at F in Fig. 31. It prevents the arc discharge from starting between anodes, but does not hinder it in starting between the mercury cathode and any of the anodes. In Fig. 34 is shown a view of the L.T. rectifier with lid raised so as to show these anode sleeves.

In addition to the six main anodes which pass through the lid of the vessel there are also two auxiliary anodes which are smaller. One of these is shown at G in Fig. 31. These serve to maintain the mercury cathode at the bottom

Digitized by Google

Digitized by Google

Digitized by Google

of the vessel " alive " or hot when the load on the main anode falls to a low level of about 40 amperes. These two auxiliaries are connected to the ends of the secondary circuit of a small ½-kilowatt transformer, and constitute

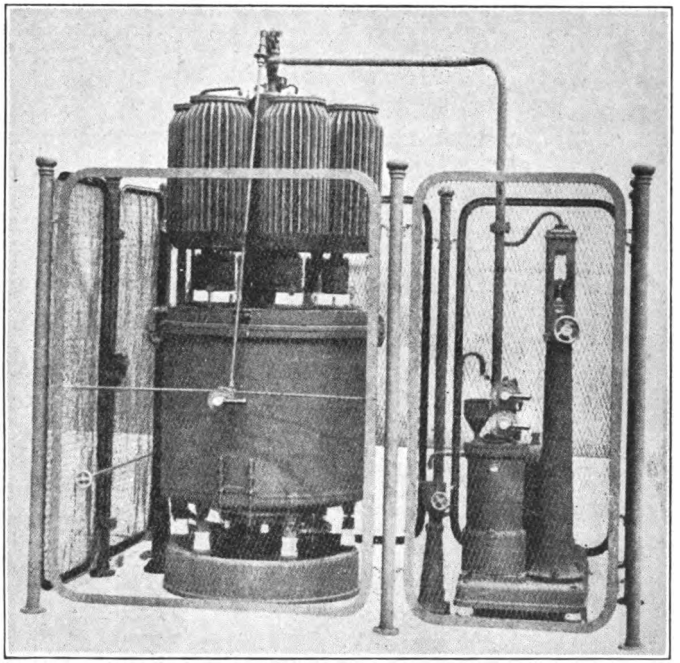
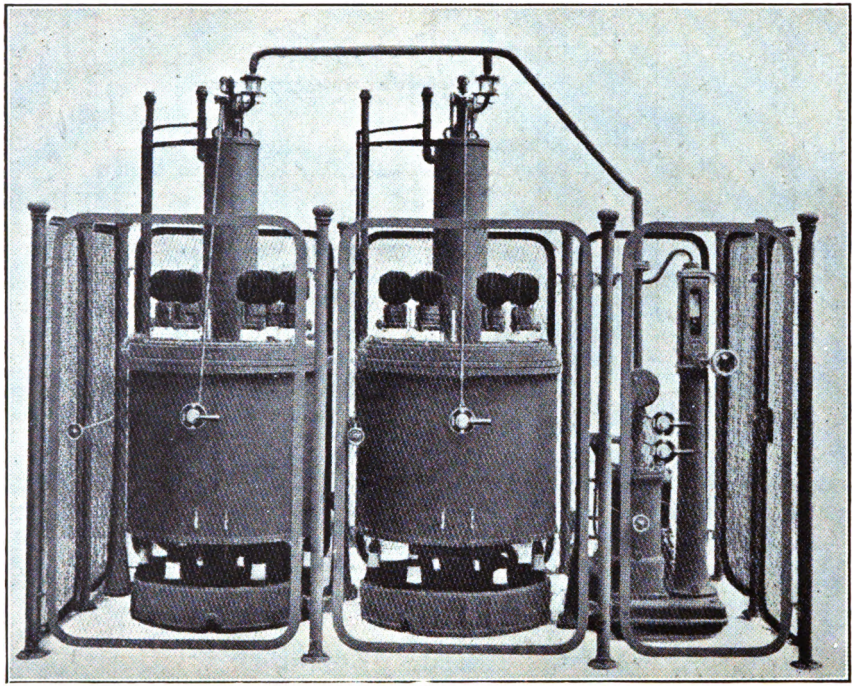


FIG. 32.—Brown, Boveri Low-tension All-metal Mercury-vapour Rectifier with Vacuum Pump on the Right Hand.

a small single-phase rectifier within the big hexaphase rectifier. There is also a rod (which passes from the top of the cooling column), the bottom end of which terminates very near to the pool of mercury which forms the cathode. This rod serves as an anode to start the rectifier when it is cold.

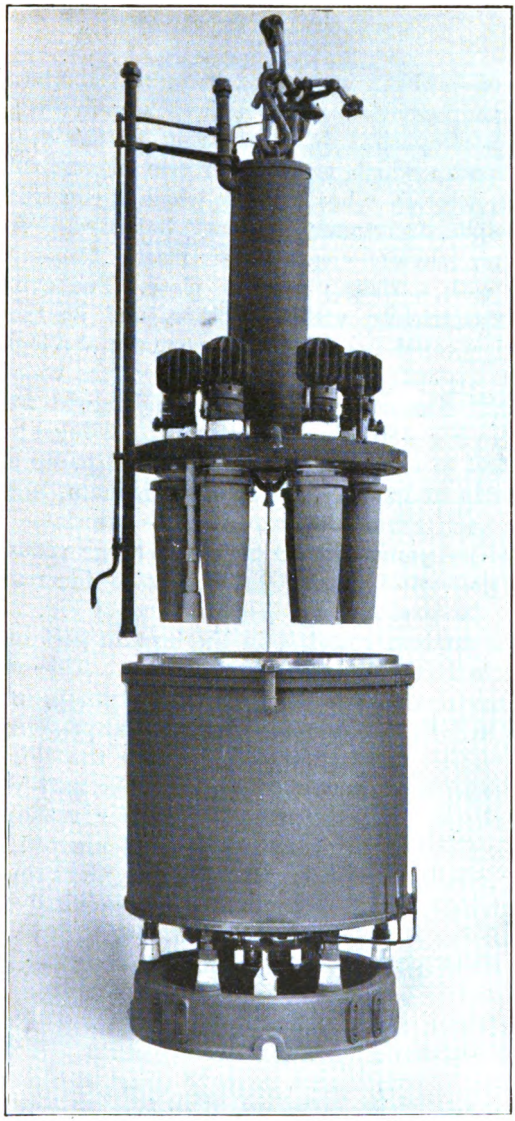
Digitized by Google



By courtesy of Messrs. Brown, Boveri & Co., Ltd.

FIG. 33.—View of the High-tension All-metal Mercury Rectifier of Messrs. Brown, Boveri & Co., Baden Switzerland.

Digitized by Google



By courtesy of Messrs. Brown, Boveri & Co., Ltd.

FIG. 34.—View of the Brown, Boveri Low-tension Mercury Rectifier with Top Lid Raised to show the Shielding Sleeves round the Anodes.

Digitized by Google

The next problem which had to be solved was that of obtaining and maintaining the high vacuum in the rectifier. This is accomplished by connecting to the rectifier a vacuum pump which is made in two parts. One part comprises a rotary " box " pump which is constructed on the principle of certain " blowers," but worked so as to exhaust air and not create an air blast. It comprises a cylinder with a sliding vane or plate. The cylinder is placed eccentrically within another, and as the inner cylinder is rotated by a ½ h.p. electric motor at a high speed the blade sweeps air in front of it out of the vessel to be exhausted. The structure will be understood from the diagram in Fig. 35b, which shows this centrifugal pump in section and in elevation. The centrifugal pump alone is not capable of making a very high vacuum, not more, perhaps, than ·02 millimetre, but it is associated with a mercury blast pump which reduces this rough vacuum to a very low pressure of ·001 to ·0001 millimetre of mercury very quickly. It is shown on the left-hand of Fig. 35a. It comprises an iron vessel *b*, in the bottom part of which mercury is boiled by an electric heater. This vessel is connected to the centrifugal vacuum pump, and the mercury in it therefore boils under reduced pressure. The vapour of this mercury rises rapidly in the closed iron cylinder and condenses at the cool upper part which is water-jacketed. As the mercury vapour rushes up it sucks air down the pipe *a* which is connected to the mercury rectifier. It acts, therefore, on the principle of the steam injector. This combined pump quickly exhausts the rectifier, and when once the necessary high vacuum is made it is not necessary to keep the vacuum going. It can be worked a little now and then as required.

The vacuum is tested by means of a MacLeod vacuum gauge, which communicates with the rectifier. It is shown in Fig. 36. It comprises a mercury vessel at the end of a flexible tube which can be raised or lowered. When the

Digitized by Google

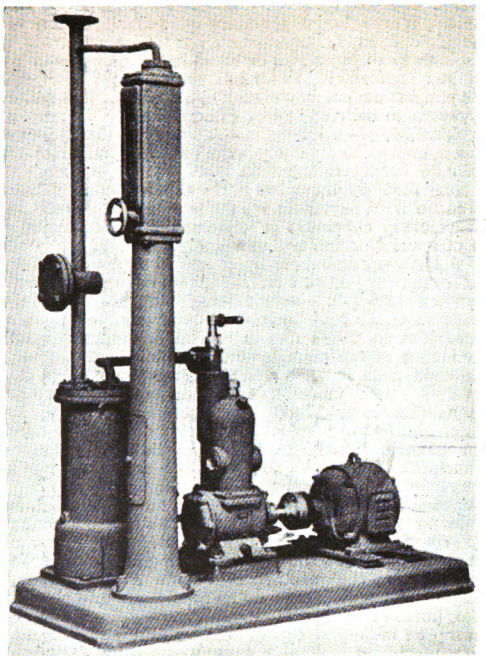


FIG. 35A.—General Appearance of the Brown, Boveri Vacuum Pump Plant.

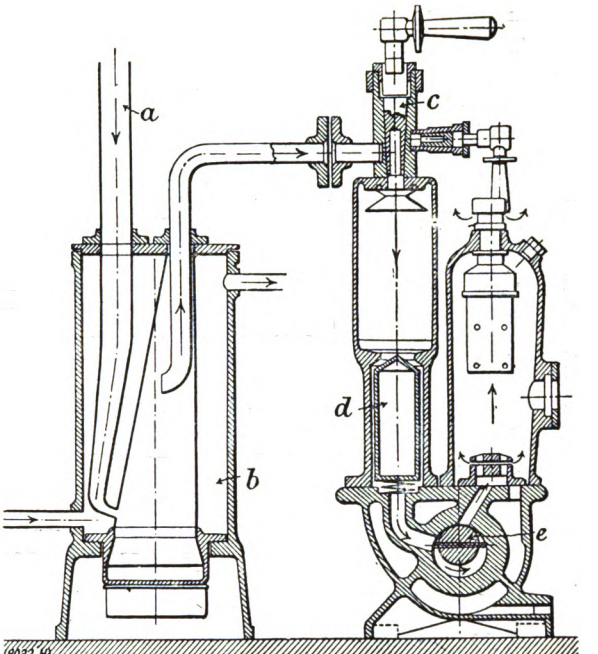


FIG. 35B.—Section of the Mercury Blast Pump and of the Rotary Auxiliary Pump.

Digitized by Google

vacuum is fairly good the mercury in the tube stands at a height above the reservoir equal to the barometric height for the time being. If the reservoir is raised a little the mercury column is caused to rise in a glass bulb ending

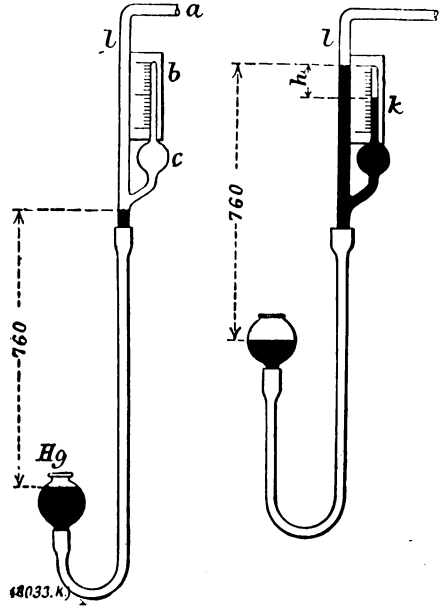


FIG. 36.—McLeod Vacuum Gauge. On the Left it is shown with the Mercury Reservoir (Hg) Lowered in Making the Vacuum, and on the Right with it Raised in Taking a Reading of Pressure.

in a closed tube *b*, and thus to compress a volume of the rarefied air into a small fraction, say, one-ten-thousandth of its original bulk. The difference in level between the mercury in the main tube and that in the little side tube, measured in millimetres, gives the pressure of the rarefied air when increased 10,000 times. Suppose this was 10 millimetres, this, then, shows that the pressure of the

Digitized by Google

rarefied air before compression was ·001 millimetres of mercury. In this manner a test is quickly made of the rectifier vacuum.

Messrs. Brown, Boveri & Co. have also devised a simple form of switchboard vacuum gauge depending on the Wheatstone Bridge principle. Let there be two fine platinum wire spirals, one of which is inside the vessel to be exhausted and one outside in air at ordinary pressure. Let the ends of these spirals be connected by two other wires of manganin so as to form a Wheatstone Bridge. (*See* Fig. 37.) Let a battery of a single storage cell and a galvanometer in the bridge circuit be arranged as usual. The battery current is arranged so as to send 152 milliamperes through the platinum wires. Then the wire which is in the vacuum will get hotter than the one outside and therefore have a higher resistance. But the other resistances can be so adjusted that the galvanometer in the bridge circuit is not deflected.

If, then, the vacuum falls off, that platinum wire which is in the vacuum becomes cooler, and the bridge balance is upset and the galvanometer deflects. Its deflection measures the badness of the vacuum. The same galvanometer can be used as an ammeter to test whether the bridge current is kept at its normal value of 152 milliamperes.

The following is a more detailed description of this B.B.C. direct reading vacuum gauge.

The whole arrangement of the direct reading measuring device consists of the following parts—

1 hot-wire vacuum gauge.
1 storage battery.
1 resistance.
1 regulating resistance.
1 shunt.
1 special fuse for 200 milliamperes
1 change-over switch.
1 precision moving coil voltmeter.

Digitized by Google

5. **Working Principle of the Hot-wire Vacuum Gauge.** Thermodynamic theory shows that the thermal conductivity of gases depends upon gas pressure. If two bodies at different temperatures are placed opposite to one another, a heat transmission takes place from the hot one to the cold one, partially by radiation and partially by conduction.

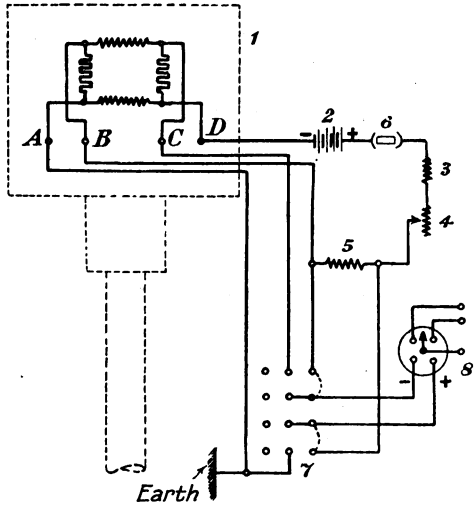


FIG. 37.—The Scheme of Circuits of the Wheatstone Bridge Vacuum Gauge of the Brown, Boveri Company, Baden.

(1) The radiation is independent of the gas pressure existing between the two bodies.

(2) The heat conductivity depends on the gas pressure. In absolute vacuum the latter is zero. At first the conductivity rises in proportion to the increasing gas pressure, but with increased pressures approaches asymptotically a constant limiting value. In the range of small gas pressures the thermal conductivity is therefore a measure of the gas pressure.

Digitized by Google

The hot-wire Brown, Boveri vacuum gauge consists of four resistance wires connected together to form a Wheatstone Bridge. The wires BC and AD (*see* Fig. 37) stretched out in the vacuum are of platinum, which changes in resistance much with temperature, and the wires AB and CD, which are exposed to the atmosphere, are of manganin or constantin, which does not change in resistance when heated. These wires are electrically heated with a constant heating current of 152 m.a. The branches BC and AD of the bridge are heated in proportion to the vacuum, their ohmic resistance rises, and at the same time the pressure difference between the points A and C increases. The exact relation between the voltmeter pressure and the gas pressure is shown by the gauge curve.

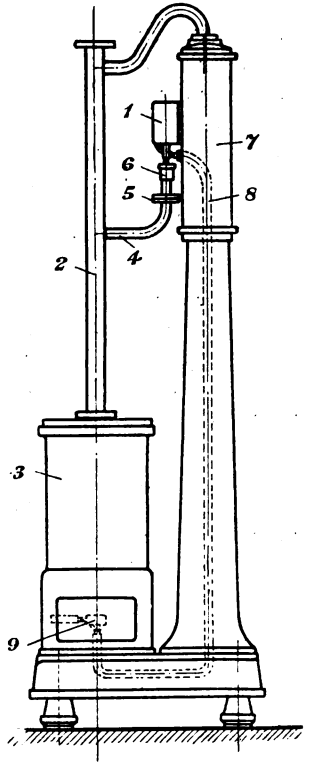


FIG. 38.—Mode of Connecting the Brown, Boveri Hot-wire Vacuum Gauge to the Vacuum Piping.

Previous to every voltmeter reading, the direct current has to be adjusted at exactly 152 m.a. On account of the special bridge connection, fluctuations of the room temperature have practically no influence on the reading of the vacuum gauge.

The milli-voltmeter is designed as contact voltmeter with adjustable minimum and maximum contacts, and

Digitized by Google

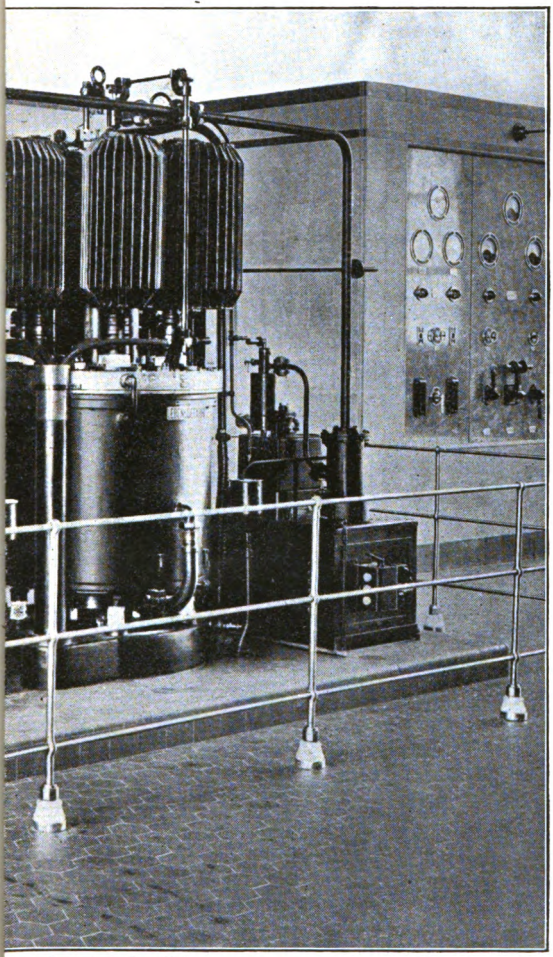
can be used for automatic control of the air pump set. For this purpose special working instructions are given.

6. **Fixing of the Hot-wire Vacuum Gauge to the Vacuum Piping.** The hot-wire vacuum gauge is connected to the vacuum piping, as shown on Fig. 38, by means of a flange and a high vacuum stuffing box. For fixing purposes the vacuum gauge must first be fitted with the stuffing box, then both parts connected with the vacuum piping, and afterwards the sealing mercury filled into the stuffing box. When removing, the flange should always be loosened at first and afterwards the stuffing box, as otherwise the mercury would penetrate into the vacuum piping. It is essential to prevent the outer and inner parts of the vacuum gauge from coming into contact with the mercury or the mercury vapours.

The four wires coming from the hot-wire vacuum gauge are led in a four-core cable along the compression vacuum gauge, and thence to the terminal board. For safe operation of the milli-voltmeter, the lead from terminal A is earthed near the change-over switch. (*See* Fig. 37.) In plants where the negative pole is earthed, the vacuum gauge has the full D.C. pressure against the cylinder, the vacuum piping and the air pump set. As long as the cylinder is under pressure, it should be touched neither from the earth nor from the insulation stool.

As the measuring device at low gas pressure is very sensitive to relatively small changes in the bridge current, the two connections from the shunt across the change-over switch to the terminals of the milli-voltmeter should not have a greater resistance than 0·05 ohm in all. Moreover, the resistance of the pressure circuit between the terminals AC of the hot-wire vacuum gauge and the terminals of the milli-voltmeter must be smaller than 0.4 ohm. It must also be observed that all the terminals must be well tightened so as to keep the intermediate resistances as small as possible. The D.C. feeding the

Digitized by Google



own, Boveri & Co., Ltd.

owatt Mercury Rectifier, in Zurich Sub-station, Furnishing lectric Street Cars.

Digitized by Google

Digitized by Google

hot-wire vacuum gauge must not be greater than 152 milli-amperes (m.a.). For this purpose a special fuse is provided which blows at 200 m.a. Its ohmic resistance is 18 ohms. It is, therefore, naturally inadmissible to replace the fuse by a simple wire or anything similar.

Previous to every reading, the value of the current supplied to the bridge must be examined to ascertain that it is exactly 152 m.a. For this purpose the change-over switch is adjusted to read current, and thus the milli-voltmeter is connected to the shunt. The resistance is now regulated until the milli-voltmeter indicates the deflection of 152 m.a. shown by the red mark. For measuring the vacuum, the change-over switch is adjusted to read voltage. The pressure is then read at the milli-voltmeter and the corresponding gas pressure is ascertained by means of a gauge curve.

The hot-wire vacuum gauge requires no attendance. The mercury in the high vacuum stuffing box should, however, be examined from time to time.

The E.M.F. of the battery is 6 volts, and its capacity 60 amps. When the voltage has dropped to 5·6 volts the battery is to be re-charged. The maximum re-charging current is about 6 amps.

The diagram in Fig. 38A will show the manner of connecting the rectifier and the various pieces of auxiliary apparatus to the three-phase circuit.

When several rectifiers have to be worked in parallel, reactance coils are connected to the anode circuits so as to drop the voltage if the current rises, and this ensures that each rectifier shall take its proper share of the load.

The illustration in Fig. 39 shows two 500-kilowatt rectifiers working in parallel in a sub-station in Zurich. This plant rectifies a portion of the three-phase supply of power from the Albula hydro-electric station near Thusis, eighty-five miles away, for working the electric cars by direct current in the City of Zurich.

Digitized by Google

The great advantages of such a rectifier plant over rotary converters are—

(1) High efficiency, 90 per cent or more over a wide range of load.

(2) Ease of operation requiring no skilled labour.

(3) No synchronizing to effect.

(4) High momentary overload capacity.

(5) Negligible maintenance costs.

(6) Low weight and no special foundations.

(7) Noiseless and without vibration.

A number of other qualifications and special advantages were set forth in a Paper by Mr. R. L. Morrison, read to Section G of the British Association meeting at Liverpool, in September, 1923, and reprinted in *Engineering* for 19th and 26th October, 1923, to which paper we have been indebted for information and illustrations concerning the Brown, Boveri all-metal mercury rectifier. These mercury rectifiers are now being used very largely for the following purposes.

(1) Rectifying three-phase currents delivered at high voltages from hydro-electric power stations for working urban and inter-urban electric street cars with direct current motors.

(2) Charging storage batteries by means of three-phase or single-phase alternating currents.

(3) Rectifying alternating currents for electrolytic work, deposition of metals, or preparation of pure metals by electrolysis.

(4) For arc-lighting by direct current arcs by means of power supplied as single- or three-phase alternating currents.

(5) Working direct current electric motors off alternating current supply stations.

Digitized by Google

CHAPTER VI

THE MERCURY-ARC AS A GENERATOR OF ELECTRIC OSCILLATIONS AND HIGH-FREQUENCY CURRENTS

1. The Mercury-vapour Lamp as a Generator of Damped Electric Oscillations. Mr. Cooper-Hewitt showed in 1902, as described in his British patent specification No. 9,206 of 1903, corresponding in date to the Convention date, 25th April, 1902, that a mercury-arc could act like a spark gap in creating electric oscillations. His arrangement was as follows—

A continuous current dynamo or high voltage battery provides a source of electromotive force, say, of 3,500 volts. In series with this is an inductance coil of large inductance and in shunt with it a condenser, and in parallel with the condenser a mercury lamp. The operation is as follows: when the high voltage is switched on to the lamp it charges the condenser, and shortly after it breaks down the cathode resistance of the mercury-vapour tube. The mercury-arc then starts, and the resistance of the lamp at once falls from many thousands of ohms to 100 or 20 ohms or less. The condenser then discharges with oscillations through the mercury tube. When, however, the current from the source of E.M.F. suddenly rises, a counter E.M.F. is opposed by the inductance coil, and as soon as the condenser is discharged the mercury-arc stops. The process then repeats itself, so that through the mercury lamp a series of damped oscillations takes place, and these may be transferred by an inductive coil or transformer to a circuit for part utilization of the energy. The method, however, has little advantages over the ordinary spark gap for the production of damped oscillations.

2. The Mercury Rectifier as a Generator of Electric

7—(5235) 12 pp.

Digitized by Google

Undamped Oscillations. The Vreeland Oscillator. Not only can the mercury-vapour bulb with two anodes of iron and a single mercury cathode act as a rectifier to convert alternating electric current into direct electric current, but it can perform the reverse process and convert direct electric current energy into alternating current. In this it resembles the three-electrode thermionic valve, which can also act both as a rectifier and as a generator.

The mercury-vapour lamp with double anode is therefore able to perform the useful service of creating electric oscillations of any desired frequency within certain limits which can be used in experiments. These oscillations are perfectly isochronous, that is, of constant frequency or time period, and, moreover, they are of true sine wave form. It is a matter of some special design to build a high-frequency alternator in which both these qualities of the alternating current produced are present, and such an alternator is generally expensive to construct. We can, however, without much difficulty build a mercury-vapour lamp which will perform the same service as a generator equivalent to a much more costly high-frequency alternator.

One type of this mercury-vapour oscillator is known as a Vreeland Oscillator, having been invented in the United States by Mr. F. K. Vreeland in 1906.[1] In this appliance a mercury-vapour bulb of the pear-shape, as used in rectifiers, is employed. It has the usual mercury cathode at the lower end, and mercury starting anode as shown in Fig. 13 of Chapter IV of this book. It has also two lateral tube extensions for the iron anodes, as in the single-phase mercury rectifier already described.

Embracing the tube are two coils of insulated wire with their planes parallel to the plane containing the anode, and these coils are joined in series so that a current flows

[1] See Mr. F. K. Vreeland on "A Sine Wave Electrical Oscillator of the Organ Pipe Type," *Physical Review*, October, 1908, also U.S.A. Patents Nos. 829,934 and 829,447, 28th August, 1906.

Digitized by Google

in the same direction round both of them. (*See* Fig. 40.) These coils, when traversed by an electric current, create a magnetic field which is perpendicular to the plane in which the electric discharge takes place in the bulb between cathode and anodes.

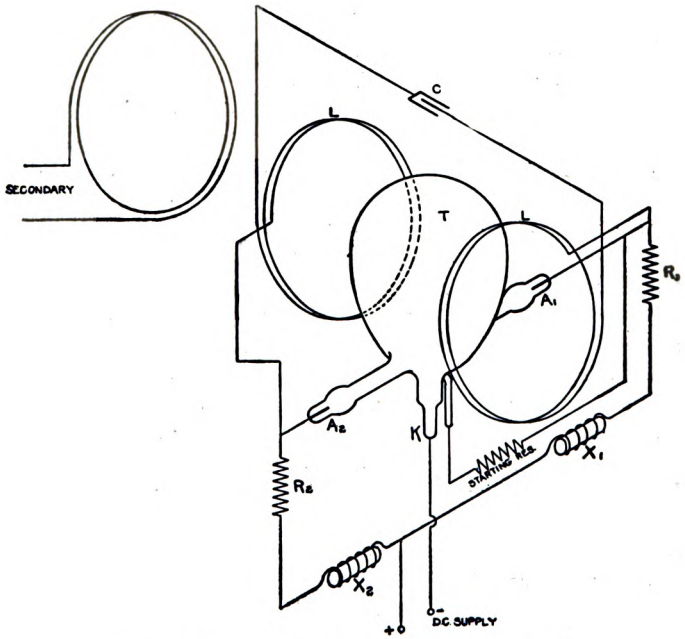


FIG. 40.—Scheme of Circuits in the Vreeland Oscillator.

In series with these coils of wire is a condenser of a certain capacity, which can be varied in capacity between wide limits. The coils are constructed of wire of low resistance, but have inductance, and this inductance, in series with the capacity, creates an oscillatory circuit having a certain natural time period of electric oscillation dependent upon the inductance L and the capacity C of the circuit.

Digitized by Google

If this inductance L is measured in millihenrys, and the capacity of the condenser in microfarads, then the frequency n of the free oscillations which can be set up in the circuit is given by the rule

$$n = \frac{5033}{\sqrt{C_{mfds} \times L_{mhys}}}$$

where C_{mfds} means the capacity of the condenser measured in microfarads, and L_{mhys} the inductance of the coils measured in millihenrys. The coils of wire are divided into sections so that the number of turns employed can be varied, and with it the inductance of the circuit, and also the condenser is divided into sections so that the capacity employed can also be changed. Therefore within the limits of the appliances we can "tune" the circuit connecting the anodes to any required frequency. The anodes are then connected together through two resistance coils and two inductive resistances, and from the connecting lead a wire proceeds to the positive terminal of the direct electric supply. (*See* Fig. 41.) Then also the mercury cathode of the bulb is connected to the negative terminal of the supply. There is also a secondary circuit which is placed in contiguity to the coils embracing the bulb.

The action of the generator is as follows: Assume the arc started in the bulb between the cathode and the starting electrode by tilting the bulb and then restoring it to a vertical position, an arc then starts to one or other of the two anodes. The connection of the circuits is such that the magnetic field of the fixed embracing coils, which we shall call the field coils, tends to deflect the electrons proceeding from the mercury cathode to the other anode, and when the arc jumps to this second anode the current is reversed in direction in the field coils, and this throws the arc back again to the first anode. The reason for this action is that when an electron or a positive ion moves in a direction at right angles to the lines of a magnetic field,

Digitized by Google

it experiences a mechanical force urging it to move in a direction at right angles to both the direction of the field and the direction of its initial motion. Hence the arc in the bulb is caused to jump backwards and forwards from one anode to the other, and the action is assisted by the natural frequency of the condenser and coil circuit. The general appearance of one type of Vreeland Oscillator is

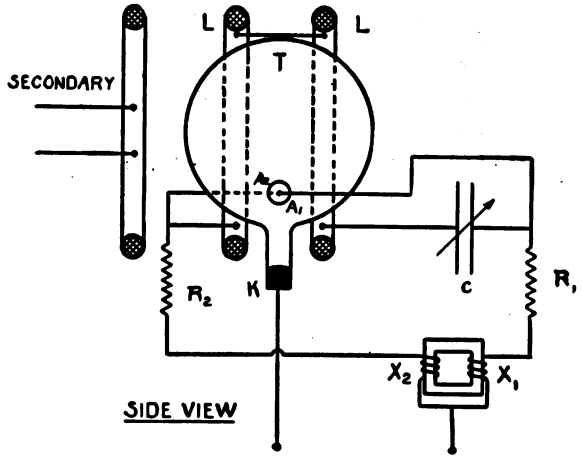


FIG. 41.—Circuits of the Vreeland Oscillator and Mercury-vapour Generator.

shown in Fig. 42, but the mercury-vapour bulb has not come out very well in the photograph. It is actually in the middle of the circular coils seen on the top of the box which contains the condenser.

Such an appliance has been largely used in the United States as a means of creating pure sine curve oscillations of frequency from 100 or so up to 2,000 for telephone testing.

It is a question whether it has any great advantages over an ordinary thermionic valve oscillator, except, perhaps,

Digitized by Google

in the fact that it requires no high voltage batteries to supply the anode voltage. The Vreeland Oscillator can take its direct current from any D.C. town supply or from

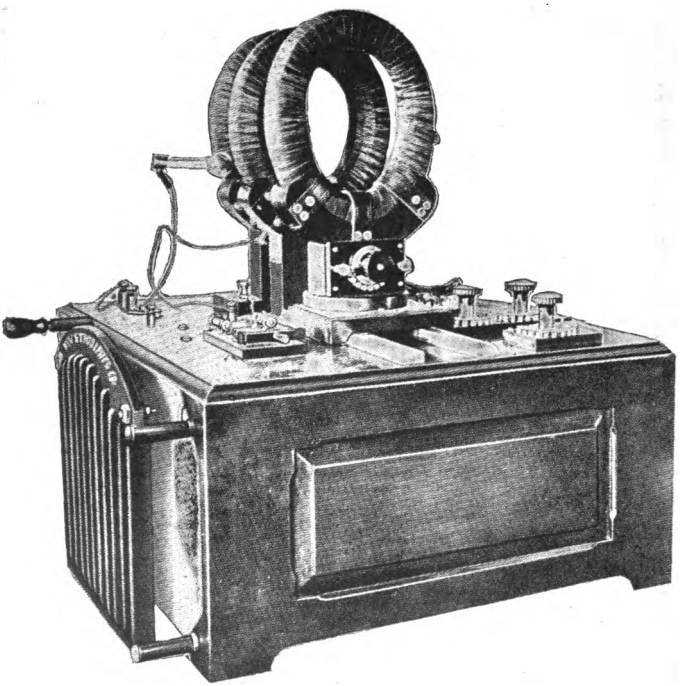


FIG. 42.—General Appearance of the Vreeland Oscillator Apparatus.
N.B.—The Mercury-vapour Bulb is not shown in this illustration but it is placed in between the Circular Coils on the top of the Condenser Box.

a storage battery without any auxiliary voltages such as are necessary in thermionic generators.

3. **Three-electrode Mercury Valves.** The reader must be presumed to have a little knowledge of the operation of the ordinary three-electrode thermionic valve used so extensively in wireless telephony. It comprises a bulb of

Digitized by Google

glass or other material highly exhausted of its air. It contains a filament, generally of tungsten, rendered incandescent by a battery, and this emits electrons copiously when incandescent. The filament is surrounded by a spiral of wire called a grid, and that again by a metal cylinder called the plate. The grid and plate are connected by wires sealed through the glass with terminal pins. A battery of cells called a high-tension (H.T.) battery has its negative pole connected to the filament and its positive pole to the plate and a current flows in this circuit called the thermionic or plate current. If, then, the grid is made negative with respect to the mean voltage of the filament, the plate current decreases or becomes zero. If it is made positive, the plate current increases up to a certain limit called the saturation value.

In the case of this thermionic valve the space between the filament, grid, and plate is full of electrons, and there are no positive ions if the vacuum is as good as it should be. This space permits negative electricity (electrons) to move only in one direction, viz. from filament to grid or plate, but not in the opposite direction. It was therefore called a *thermionic valve* by the author, who invented, in 1904, the two-electrode form with filament and plate only. The current in the high vacuum or hard valve as it is called is carried only by electrons in motion.

4. We can try a similar construction with a mercury-vapour lamp by placing a grid or wire mesh or perforated plate across the bulb or tube (*see* Fig. 43), as was first done by M. Maurice Leblanc[1], and demonstrate the following facts. If we set the mercury-arc in action as usual and then make the grid *b* (*see* Fig. 43) negative by a battery, the grid will not take a negative charge because it at once attracts to it positive mercury ions, and these nullify its negative potential. If we provide a second or auxiliary

[1] See *Comptes Rendus de l'Academie des Sciences*, 17th July, 1922, Vol. 175, p. 132.

Digitized by Google

anode *d* so as to keep the cathode *c* alive, and keep the grid *b* negative, and then interrupt the arc current for an instant to the main anode *a*, the grid absorbs the positive ions near it and, remaining then negative, prevents the arc being re-established to the anode *a* until the grid is made positive again. We can employ this method to construct a mercury-vapour generator of electric oscillations as follows—

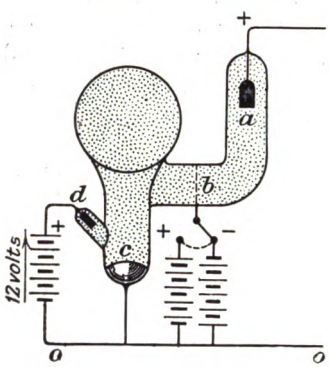


FIG. 43.—A Mercury-arc Rectifier with Mercury Cathode at *c*. From Anode at *a* and a Grid Introduced at *b* in the Bulb.

A source of direct current E (*see* Fig. 44) has its negative pole connected to the cathode of a mercury-vapour bulb and its positive terminal through a coil of large inductance *l* to its main anode *a*. There is a supplementary or maintaining anode *d* which is kept positive with regard to the cathode *c* by a supplementary battery. The main anode *a* is also connected with the cathode *c* through an oscillatory circuit comprising a condenser of capacity C and a coil of inductance L, connected through the primary coil P of a transformer P.S. In addition there is a battery *h* for making the grid *b* of the bulb negative.

Suppose, then, that the mercury-arc is started and that the grid is made negative by the grid battery. If the arc current is stopped for an instant, the grid being then negative, the arc cannot restart itself to the anode *a*, but continues to discharge to the anode *d*. The source of voltage E then charges up the condenser C, and as soon as the positive potential of the condenser on the side next to the anode *a* rises above the value of the negative potential

Digitized by Google

given to the grid by the grid battery the arc starts again to a, and that causes the condenser to discharge through the mercury-arc with oscillations. It is possible to arrange the various inductances, voltages, and capacity so that the oscillations of the condenser persist without damping, and then the whole arrangement becomes a generator of high-frequency oscillations with a frequency $1/2\pi\sqrt{CL}$ where C is the capacity of the condenser and L the inductance of its associated coil. The use of the coil of large inductance is to create an extra electromotive force in the oscillation circuit to charge up the condenser to a high potential at the moment when the main arc discharge in the bulb is arrested.

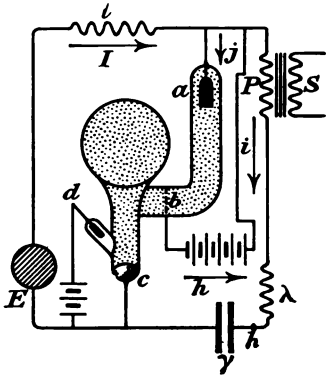


FIG. 44.

The special difficulty with all these devices in which a metal grid is placed in the path of the arc in a mercury-vapour bulb is that the grid soon becomes hot, and then acts at once as a cathode to the main anode a. To prevent this the grid has to be constructed of a metal tube through which water flows to keep it cool.

There are, however, a variety of ways in which the mercury-vapour arc can be made to generate electric oscillations.

Owing to the presence of the positive ions of mercury in the bulb and to the heat generated in it, these methods are not so simple or convenient as those depending on the use of a pure electron discharge in the thermionic valve. The mercury-arc may therefore be distinguished from the latter by calling it an ionic valve, to indicate that there are positive ions as well as electrons in the bulb.

Digitized by Google

Conclusion. It will be evident from the descriptions given of the structure and operation of the mercury-vapour rectifier that we have in this appliance a most valuable addition to the resources of the electrical engineer and one which in efficiency and robustness stands on a level with the dynamo, motor or static transformer.

The reader who desires more detailed information on this appliance from the point of view of the practical electrical engineer and also valuable criticisms, may be referred to a paper by **Mr.** G. Rogers, on "Automatic and Semi-automatic Mercury-vapour Rectifier Sub-stations," and the discussion thereon, in the *Journal* of the Institution of Electrical Engineers, London, Vol. 63, February, 1925, p. 157, which contains much information of importance on this matter.

Digitized by Google

INDEX

ALTERNATING currents, rectification of, 48
Anode sleeve, in Brown, Boveri all metal rectifier, 76
Arc, characteristic curves of the, 22
—— discharge, phenomena of the, 17
—— light carbons, 15
——, the electric-, 19
Atom, an, 2
——, a neutral, 4
Atoms and electrons, 8
Atomic constitution of electricity, 3
—— constitution of matter, 1
—— number, definition of the, 5
—— weight, definition of the, 5
Atoms, structure of, 3
Automatic mercury lamp, 31

BOHR, NIELS, 7
Bohr-Rutherford, theory of atomic structure, 7
Brown, Boveri all-metal rectifier, 75
—— —— —— mercury - vapour rectifiers, 72
—— —— —— mercury - vapour rectifier, section of the, 77
—— —— mercury-vapour rectifiers at Zurich, 87
—— —— hot-wire vacuum gauge, 83

CHARACTERISTIC curves of the electric-arc, 22
Comparison of the efficiency of a rotary converter and a mercury-arc rectifier, 58
Cooper Hewitt mercury-vapour lamp, hand started, 25, 30
—— —— patents, 24, 59
Crookes, Sir William, 10

DARK space, the Crookes, 10
Davy, Sir Humphry, 14
Dufay, C. F. de, 3

EFFICIENCY, curves of mercury-vapour rectifier, 58, 64, 65
—— of the mercury-vapour lamp, 33
—— —— mercury-vapour rectifier, 56
Electric-arc discharge, the, 13
——, first production of the, by Davy, 14
—— lamps, self-regulating, 15, 16
——, radiation from the, 18
——, transport of electrons in the, 21
Electricity, atomic nature of, 3
Electrons, definition of the term, 2
Electric discharge, varieties of, 10
Electrical engineering and mercury-vapour rectifiers, 60
Electron, mass of an, 6, 7
Electricity, nature of, 1
Energy, electricity not a form of, 2
——, formula for the relation of rectified, to applied voltage in case of three-phase mercury-vapour rectifier, 49, 55

FOUCAULT, J. B. L., 15

GLOW discharge, the, 10
Greener, W., 15

HAND-STARTED mercury lamp starting, 31

Digitized by Google

Hewittic Company's substation rectifying plant, 65, 66
—— —— three-phase mercury-vapour rectifier 50
Hewittic Electric Company's glass bulb rectifier, 61, 62
—— —— Company, the, 30, 61
Hewitt, Peter Cooper, 24, 42
Hexaphase mercury rectifier, 52
Hot-wire vacuum gauge, 84
Hydrogen, number of atoms in 1 c.c. of, 6

K.B.B. mercury vapour lamp, the, 40
Kromayer mercury-vapour arc lamp, the, 37

LEBLANC, Maurice, 95
Low tension mercury-vapour rectifier of Brown, Boveri, 77
Luminous efficiency of the mercury-vapour lamp, 34, 35

MATTER, atomic constitution of,
McLeod vacuum gauge, 82 [1
Mercury-arc generators of high-frequency electric currents, 89
——, production of the, 24
—— rectifier, the, 42
——, the, 24
Mercury atom, the, 27
—— cathode, a, 26
——, properties of, 24
—— rectifier, single-phase, 44
—— —— ——, with auxiliary anodes, 63
—— transformed into gold, 41
—— -vapour arc lamps banked for photography, 36
—— lamps for medical purposes, 40
—— rectifier in electrical engineering, 60
Miethe, Professor, 40
Modern views of atomic structure, 4
Molecule, a, 2
Morrison, R. L., 59

PROTON, definition of the term, 2

QUANTUM path, 8

RADIATION from atoms, 9
Ratio of direct and alternating current voltage in case of the mercury-vapour rectifier, 57
Rectification of alternating electric currents of a mercury-vapour lamp, 44, 45
—— —— —— ——, explanation of, 51
Rectifier plant, the Hewittic Company's, 64
——, the mercury-vapour, 44
Rotary converters and mercury-vapour rectifiers, comparison of efficiency of, at various loads, 58
Rutherford, Sir Ernest, 7

SHIFTER, Definition of a, 32
Silica-tube mercury-vapour arc lamp, 35
Spark discharge, the, 11
—— voltage, 12
Spectrum of the mercury-vapour arc, 28
Staite, W. E., 15
Stammreich, H., 40
Sub-station rectifiers, the Hewittic, 66

THOMSON, Sir Joseph, 6, 11
Three-electrode mercury valves, 94 [49
Three-phase mercury rectifier,
Transmission of electricity through gases, 1

UNILATERAL conductivity of mercury vapour, 42

VACUUM pump used with Brown, Boveri all-metal mercury-vapour rectifiers, 80
Vacuum-tight joint in, 75
Vreeland, F. R., 90
—— oscillator, 90

PRINTED IN GREAT BRITAIN AT THE PITMAN PRESS, BATH
B5—(5235)

Digitized by Google

AN ABRIDGED LIST OF

TECHNICAL BOOKS

PUBLISHED BY

Sir Isaac Pitman & Sons, Ltd.

(Incorporating WHITTAKER & CO.)

PARKER STREET, KINGSWAY,

LONDON, W.C.2

The prices given apply only to the British Isles, and are subject to alteration without notice.

A complete Catalogue giving full details of the following books will be sent post free on application.

ALL PRICES ARE NET.

	s.	d.
ACCUMULATORS, MANAGEMENT OF. Sir D. Salomons	7	6
AEROFOILS AND RESISTANCE OF AERODYNAMIC BODIES, PROPERTIES OF. A. W. Judge	18	0
AERONAUTICS, ELEMENTARY. A. P. Thurston	8	6
AERONAUTICAL ENGINEERING, TEXTBOOK OF. A. Klemin	15	0
AEROPLANE DESIGN AND CONSTRUCTION, ELEMENTARY PRINCIPLES OF. A. W. Judge	7	6
AEROPLANES, DESIGN OF. A. W. Judge	14	0
AEROPLANE STRUCTURAL DESIGN. T. H. Jones and J. D. Frier	21	0
AIRCRAFT AND AUTOMOBILE MATERIALS—FERROUS. A. W. Judge	25	0
AIRCRAFT AND AUTOMOBILE MATERIALS—NON-FERROUS AND ORGANIC. A. W. Judge	25	0
AIRSHIP, THE RIGID. E. H. Lewitt	30	0
ALTERNATING CURRENT BRIDGE METHODS OF ELECTRICAL MEASUREMENT. B. Hague	15	0
ALTERNATING-CURRENT CIRCUIT, THE. P. Kemp.	2	6
ALTERNATING CURRENT MACHINERY, DESIGN OF. J. R. Barr and R. D. Archibald	30	0
ALTERNATING CURRENT MACHINERY, PAPERS ON THE DESIGN OF. C. C. Hawkins, S. P. Smith, and S. Neville	21	0
ALTERNATING-CURRENT WORK. W. Perren Maycock	10	6

Digitized by Google

	s.	d.
ARCHITECTURAL HYGIENE. B. F. and H. P. Fletcher	10	6
ARITHMETIC OF ALTERNATING CURRENTS. E. H. Crapper	4	6
ARITHMETIC OF ELECTRICAL ENGINEERING. Whittaker's	3	6
ARITHMETIC OF TELEGRAPHY AND TELEPHONY. T. E. Herbert and R. G. de Wardt	5	0
ARTIFICIAL SILK AND ITS MANUFACTURE. J. Foltzer. Translated by S. Woodhouse	21	0
AUTOMOBILE AND AIRCRAFT ENGINES. A. W. Judge	30	0
AUTOMOBILE ENGINEERS, REPORT OF [THE INSTITUTE OF, ON FUELS	10	6
AUTOMOBILE IGNITION AND VALVE TIMING, STARTING, AND LIGHTING. J. B. Rathbun	8	0
BALL AND ROLLER BEARINGS, HANDBOOK OF. A. W. Macaulay	12	6
BAUDÔT PRINTING TELEGRAPH SYSTEM. H. W. Pendry	6	0
BLASTING WITH HIGH EXPLOSIVES. W. G. Boulton	5	0
BLUE PRINTING AND MODERN PLAN COPYING. B. J. Hall	6	0
BLUE PRINT READING. J. Brahdy	10	6
BREWING AND MALTING. J. Ross Mackenzie	8	6
B.S.A., BOOK OF THE	2	0
CABINET MAKING, ART AND CRAFT OF. D. Denning	7	6
CALCULUS FOR ENGINEERING STUDENTS. J. Stoney	3	6
CAMERA LENSES. A. W. Lockett	2	6
CARBURETTOR HANDBOOK. E. W. Knott	10	6
CARPENTRY AND JOINERY. B. F. and H. P. Fletcher	10	6
CERAMIC INDUSTRIES POCKET BOOK. A. B. Searle	8	6
CHEMICAL ENGINEERING, INTRODUCTION TO. A. F. Allen	10	6
CHEMISTRY, A FIRST BOOK OF. A Coulthard	3	0
CLUTCHES, FRICTION. R. Waring-Brown	5	0
COLLIERY ELECTRICAL ENGINEERING. G. M. Harvey	15	0
COLOUR IN WOVEN DESIGN: A TREATISE ON TEXTILE COLOURING. R. Beaumont	21	0
COMPRESSED AIR POWER. A. W. and Z. W. Daw	21	0
CONTINUOUS-CURRENT DYNAMO DESIGN, ELEMENTARY PRINCIPLES OF. H. M. Hobart	10	6
CONTINUOUS CURRENT MOTORS AND CONTROL APPARATUS. W. Perren Maycock	7	6
COSTING ORGANIZATION FOR ENGINEERS. E. W. Workman	3	6
COTTON-SPINNERS' POCKET BOOK, THE. J. F. Innes	3	6

Digitized by Google

	s.	d.
DETAIL DESIGN OF MARINE SCREW PROPELLERS. D. H. Jackson	6	0
DIRECT CURRENT DYNAMO AND MOTOR FAULTS. R. M. Archer	7	6
DIRECT CURRENT ELECTRICAL ENGINEERING. J. R. Barr	15	0
DIRECT CURRENT ELECTRICAL ENGINEERING, THE ELEMENTS OF. H. F. Trewman and G. E. Condliffe	5	0
DRAWING AND DESIGNING. C. G. Leland	3	6
DRAWING, MANUAL INSTRUCTION. S. Barter	4	0
DRAWING OFFICE PRACTICE. H. P. Ward	7	6
DRESS, BLOUSE, AND COSTUME CLOTHS, DESIGN AND FABRIC MANUFACTURE OF. R. Beaumont	42	0
DYNAMO, HOW TO MANAGE THE. A. E. Bottone	2	0
DYNAMO: ITS THEORY, DESIGN, AND MANUFACTURE, THE. C. C. Hawkins. Vol. I	21	0
Vol. II	15	0
ELECTRIC ARC AND OXY-ACETYLENE WELDING. E. A. Atkins	7	6
ELECTRIC BELLS. S. R. Bottone	3	6
ELECTRIC CIRCUIT THEORY AND CALCULATIONS. W. Perren Maycock	10	6
ELECTRIC GUIDES, HAWKINS'. 10 volumes, each	5	0
ELECTRIC LIGHTING AND POWER DISTRIBUTION. Vol. I. W. Perren Maycock	10	6
Vol. II	10	6
ELECTRIC LIGHTING IN THE HOME. L. Gaster		6
ELECTRIC LIGHTING IN FACTORIES. L. Gaster and J. S. Dow		6
ELECTRIC LIGHT FITTING: A TREATISE ON WIRING FOR LIGHTING, HEATING, &c. S. C. Batstone	6	0
ELECTRIC LIGHT FITTING, PRACTICAL. F. C. Allsop	7	6
ELECTRIC MINING MACHINERY. S. F. Walker	15	0
ELECTRIC MOTORS AND CONTROL SYSTEMS. A. T. Dover	15	0
ELECTRIC MOTORS—DIRECT CURRENT. H. M. Hobart	15	0
ELECTRIC MOTORS—POLYPHASE. H. M. Hobart	15	0
ELECTRIC MOTORS, A SMALL BOOK ON. C.C. AND A.C. W. Perren Maycock	6	0
ELECTRIC TRACTION. A. T. Dover	21	0
ELECTRIC WIRING, FITTINGS, SWITCHES, AND LAMPS. W. Perren Maycock	10	6
ELECTRIC WIRING DIAGRAMS. W. Perren Maycock	5	0
ELECTRIC WIRING TABLES. W. Perren Maycock	3	6

Digitized by Google

	s.	d.
ELECTRICAL ENGINEERS' POCKET BOOK. Whittaker's	10	6
ELECTRICAL INSTRUMENT MAKING FOR AMATEURS. S. R. Bottone	6	0
ELECTRICAL INSTRUMENTS IN THEORY AND PRACTICE. Murdoch and Oschwald	12	6
ELECTRICAL MACHINES, PRACTICAL TESTING OF. L. Oulton and N. J. Wilson	6	0
ELECTRICAL POWER ENGINEERS' LIBRARY. Three volumes, each 7s. 6d.; Complete set	20	0
ELECTRICAL TECHNOLOGY. H. Cotton	12	6
ELECTRICAL TERMS, DICTIONARY OF. S. R. Roget	7	6
ELECTRICAL TRANSMISSION OF PHOTOGRAPHS. M. J. Martin	6	0
ELECTRICITY. R. E. Neale	3	0
ELECTRICITY AND MAGNETISM, FIRST BOOK OF. W. Perren Maycock	6	0
ELECTRO MOTORS: HOW MADE AND HOW USED. S. R. Bottone	4	6
ELECTROLYTIC RECTIFIERS. N. A. de BRUYNE	3	6
ELECTRO-PLATERS' HANDBOOK. G. E. Bonney	5	0
ELECTRO-TECHNICS, ELEMENTS OF. A. P. Young	5	0
ENGINEER DRAUGHTSMEN'S WORK: HINTS TO BEGINNERS IN DRAWING OFFICES	2	6
ENGINEERING SCIENCE, PRIMER OF. E. S. Andrews. Part 1, 2s. 6d.; Part 2, 2s.; Complete	3	6
ENGINEERING WORKSHOP EXERCISES. E. Pull	3	6
ENGINEERS' AND ERECTORS' POCKET DICTIONARY: ENGLISH, GERMAN, DUTCH. W. H. Steenbeek	2	6
ENGLISH FOR TECHNICAL STUDENTS. F. F. Potter	2	0
FIELD MANUAL OF SURVEY METHODS AND OPERATIONS. A. Lovat Higgins	21	0
FIELD WORK FOR SCHOOLS. E. H. Harrison and C. A. Hunter	2	0
FILES AND FILING. Fremont and Taylor	21	0
FITTING, PRINCIPLES OF. J. G. Horner	7	6
FIVE FIGURE LOGARITHMS. W. E. Dommett	1	6
FLAX CULTURE AND PREPARATION. F. Bradbury	10	6
FUEL ECONOMY IN STEAM PLANTS. A. Grounds	5	0
FUEL OILS AND THEIR APPLICATIONS. H. V. Mitchell	5	0
FUSELAGE DESIGN. A. W. Judge	3	0
GAS, GASOLINE, AND OIL ENGINES. J. B. Rathbun	8	0
GAS ENGINE TROUBLES AND INSTALLATIONS. J. B. Rathbun	8	0

Digitized by Google

	s.	d.
GAS AND OIL ENGINE OPERATION. J. Okill	5	0
GAS, OIL, AND PETROL ENGINES: INCLUDING SUCTION GAS PLANT AND HUMPHREY PUMPS. A. Garrard	6	0
GEOMETRY, THE ELEMENTS OF PRACTICAL PLANE. P. W. Scott	4	0
GEOLOGY, ELEMENTARY. A. J. Jukes-Browne	3	0
GRAPHIC STATICS, ELEMENTARY. J. T. Wight	5	0
HANDRAILING FOR GEOMETRICAL STAIRCASES. W. A. Scott	2	6
HIGH HEAVENS, IN THE. Sir R. Ball	5	0
HIGHWAY ENGINEER'S YEAR BOOK. H. G. Whyatt.	6	0
HOSIERY MANUFACTURE. W. Davis	7	6
HYDRAULICS. E. H. Lewitt	8	6
ILLUMINANTS AND ILLUMINATING ENGINEERING, MODERN. Dow and Gaster	25	0
INDICATOR HANDBOOK. C. N. Pickworth	7	6
INDUCTION COILS. G. E. Bonney	6	0
INDUCTION COIL, THEORY OF THE. E. Taylor-Jones	12	6
IONIC VALVE, GUIDE TO STUDY OF THE. W. D. Owen	2	6
IRONFOUNDING, PRACTICAL. J. G. Horner	10	0
IRON, STEEL AND METAL TRADES, TABLES FOR THE. J. Steel	3	6
KINEMATOGRAPHY (PROJECTION), GUIDE TO. C. N. Bennett	10	6
LACQUER WORK. G. Koizumi	15	0
LEATHER WORK. C. G. Leland	5	0
LEKTRIK LIGHTING CONNECTIONS. W. Perren Maycock	1	0
LENS WORK FOR AMATEURS. H. Orford	3	6
LIGHTNING CONDUCTORS AND LIGHTNING GUARDS. Sir O. Lodge	15	0
LOGARITHMS FOR BEGINNERS. C. N. Pickworth	1	6
MACHINE DRAWING, PREPARATORY COURSE TO. P. W. Scott	2	0
MAGNETISM AND ELECTRICITY, AN INTRODUCTORY COURSE OF PRACTICAL. J. R. Ashworth	3	0
MAGNETO AND ELECTRIC IGNITION. W. Hibbert	3	6
MANURING LAND, TABLES FOR MEASURING AND. J. Cullyer	3	0
MARINE ENGINEERS, PRACTICAL ADVICE FOR. C. W. Roberts	5	0
MARINE SCREW PROPELLERS. DETAIL DESIGN OF. D. H. Jackson	6	0

Digitized by Google

	s.	d.
MATHEMATICAL TABLES. W. E. Dommett	4	6
MATHEMATICS, MINING (PRELIMINARY). G. W. Stringfellow. With Answers	2	0
MECHANICAL ENGINEERING DETAIL TABLES. J. P. Ross	7	6
MECHANICAL ENGINEERS' POCKET BOOK. Whittaker's	12	6
MECHANICAL REFRIGERATION. H. Williams	20	0
MECHANICAL STOKING. D. Brownlie	5	0
MECHANICAL TABLES	2	0
MECHANICS' AND DRAUGHTSMEN'S POCKET BOOK. W. E. Dommett	2	6
METAL TURNING. J. G. Horner	6	0
METAL WORK, PRACTICAL SHEET AND PLATE. E. A. Atkins	7	6
METAL WORK—REPOUSSÉ. C. G. Leland	5	0
METALWORKERS' PRACTICAL CALCULATOR. J. Matheson	2	0
METRIC AND BRITISH SYSTEMS OF WEIGHTS AND MEASURES. F. M. Perkin	3	6
METRIC CONVERSION TABLES. W. E. Dommett	2	6
MILLING, MODERN. E. Pull	9	0
MINERALOGY. F. H. Hatch	6	0
MINING, MODERN PRACTICE OF COAL. Kerr and Burns. Part 1, 5/-; Parts 2, 3 and 4, each	6	0
MINING SCIENCE, JUNIOR COURSE IN. H. G. Bishop	2	6
MOTION PICTURE OPERATION, STAGE ELECTRICS, ETC. H. C. Horstmann and V. H. Tousley	7	6
MOTOR TRUCK AND AUTOMOBILE MOTORS AND MECHANISM. T. H. Russell	8	0
MOTOR BOATS, HYDROPLANES AND HYDROAEROPLANES. T. H. Russell	8	0
MUSIC ENGRAVING AND PRINTING. W. Gamble	21	0
NAVAL DICTIONARY, ITALIAN-ENGLISH AND ENGLISH-ITALIAN. W. T. Davis	10	6
OPTICS OF PHOTOGRAPHY AND PHOTOGRAPHIC LENSES. J. T. Taylor	4	0
PATENTS FOR INVENTIONS. J. E. Walker and R. B. Foster	21	0
PATTERN-MAKING, PRINCIPLES OF. J. G. Horner	4	0
PLAN COPYING IN BLACK LINES FOR HOT CLIMATES. B. J. Hall	2	6
PLYWOOD AND GLUE, MANUFACTURE AND USE OF, THE. B. C. Boulton	7	6
POLYPHASE CURRENTS. A. Still	7	6

Digitized by Google

	s.	d.
POWER STATION EFFICIENCY CONTROL. J. Bruce.	12	6
POWER WIRING DIAGRAMS. A. T. Dover . .	6	0
PRINTING. H. A. Maddox	5	0
QUANTITIES AND QUANTITY TAKING. W. E. Davis	6	0
RADIO COMMUNICATION, MODERN. J. H. Reyner	5	0
RADIO YEAR BOOK	1	6
RAILWAY ELECTRIFICATION. H. F. Trewman .	25	0
RAILWAY TECHNICAL VOCABULARY. L. Serraillier	7	6
RALEIGH HANDBOOK, THE. Mentor . . .	2	0
REFRACTORIES FOR FURNACES, CRUCIBLES, ETC. A. B. Searle	5	0
REINFORCED CONCRETE. W. N. Twelvetrees .	21	0
REINFORCED CONCRETE BEAMS AND COLUMNS, PRACTICAL DESIGN OF. W. N. Twelvetrees .	7	6
REINFORCED CONCRETE MEMBERS, SIMPLIFIED METHODS OF CALCULATING. W. N. Twelvetrees	5	0
REINFORCED CONCRETE, DETAIL DESIGN IN. E. S. Andrews	6	0
ROSES AND ROSE GROWING. R. G. Kingsley .	7	6
RUSSIAN WEIGHTS AND MEASURES, TABLES OF. Redvers Elder	2	6
SHOT-GUNS. H. B. C. Pollard	6	0
SLIDE RULE. A. L. Higgins		6
SLIDE RULE. C. N. Pickworth . . .	3	6
SOIL, SCIENCE OF THE. C. Warrell . . .	3	6
STEAM TURBINE THEORY AND PRACTICE. W. J. Kearton	15	0
STEAM TURBO-ALTERNATOR, THE. L. C. Grant .	15	0
STEELS, SPECIAL. T. H. Burnham . . .	5	0
STEEL WORKS ANALYSIS. J. O. Arnold and F. Ibbotson	12	6
STORAGE BATTERY PRACTICE. R. Rankin . .	7	6
SURVEYING AND SURVEYING INSTRUMENTS. G. A. T. Middleton	6	0
SURVEYING, TUTORIAL LAND AND MINE. T. Bryson	10	6
TELEGRAPHY. T. E. Herbert	18	0
TELEGRAPHY, ELEMENTARY. H. W. Pendry .	7	6
TELEPHONE HANDBOOK, PRACTICAL. J. Poole .	15	0
TELEPHONES, AUTOMATIC. F. A. Ellson . .	5	0

Digitized by Google

	s.	d.
TELEPHONY. T. E. Herbert	18	0
TEXTILE CALCULATIONS. G. H. Whitwam . .	25	0
TRANSFORMER PRACTICE, THE ESSENTIALS OF. E. G. Reed	12	6
TRIGONOMETRY FOR ENGINEERS, PRIMER OF. W. G. Dunkley	5	0
TURRET LATHE TOOLS, HOW TO LAY OUT . .	6	0
UNION TEXTILE FABRICATION. R. Beaumont .	21	0
VENTILATION, PUMPING, AND HAULAGE, THE MATHEMATICS OF. F. Birks	5	0
VOLUMETRIC ANALYSIS. J. B. Coppock . .	3	6
WATER MAINS, THE LAY-OUT OF SMALL. H. H. Hellins	7	6
WATERWORKS FOR URBAN AND RURAL DISTRICTS. H. C. Adams	15	0
WEAVING FOR BEGINNERS. L. Hooper . .	5	0
WEAVING WITH SMALL APPLIANCES. L. Hooper (1) THE WEAVING BOARD. (2) TABLET WEAVING. (3) TABLE LOOM WEAVING. Each . .	7	6
WIRELESS POCKET BOOK, MARINE. W. H. Marchant	6	0
WIRELESS TELEGRAPHY AND TELEPHONY, AN INTRODUCTION TO. J. A. Fleming . . .	3	6
WIRELESS TELEGRAPHY. W. H. Marchant .	7	6
WOOD-BLOCK PRINTING. F. Morley Fletcher .	8	6
WOODCARVING. C. G. Leland	7	6
WOODWORK, MANUAL INSTRUCTION. S. Barter .	7	6
WOOLLEN YARN PRODUCTION. T. Lawson .	3	6
WOOL SUBSTITUTES. R. Beaumont . . .	10	6
WORKSHOP GAUGES. L. Burn and G. F. F. Eagar	5	0

Complete Descriptive Catalogue of Scientific and Technical Books post free.

LONDON: SIR ISAAC PITMAN & SONS, LTD.
PARKER STREET, KINGSWAY, W.C.2

Digitized by Google

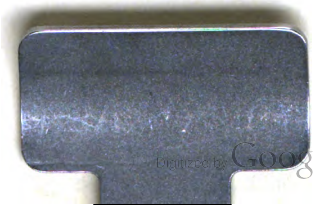
Digitized by Google

89097935902

B89097935902A

Digitized by Google

175
X



Digitized by Google

89097935902

b89097935902a

Digitized by Google